Lateral termination of the north-directed Alpine orogeny and onset of westward escape in the Western Alpine arc: Structural and sedimentary evidence from the external zone

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[1] The initial propagation of the Western Alpine orogen was directed northwestward, as shown by basement-involved and Mesozoic sedimentary cover compressional structures and by the early foreland basins evolution. The crystalline basement of the Dauphiné zone recorded three shortening episodes: pre-Priabonian deformation D1 (coeval with the Pyrenean-Provence orogeny), and Alpine shortening events D2 (N-NW directed) and D3 (W-directed). The early Oligocene D2 structures are trending sub-perpendicular to the more recent, arcuate orogen and are interfering with (or truncated by) D3, which marks the onset of westward lateral extrusion. The NW-ward propagating Alpine flexural basin shows earliest Oligocene thin-skinned compressional deformation, with syn-depositional basin-floor tilting and submarine removal of the basin infill above active structures. Gravity enhanced submarine erosion gave birth locally to steep submarine slopes overlain by kilometric-scale blocks slid from the orogenic wedge. The deformations of the basin floor and the associated sedimentary and erosional features indicate a N-NW-ward directed propagation, consistent with D2 in the Dauphiné foreland. The Internal zones represent the paleo-accretionary prism developed during this early Alpine continental subduction stage. The early buildup has been curved in the arc and rapidly exhumed during the Oligocene collision stage. Westward extrusion and indenting by the Apulian lithosphere allowed the modern arc to crosscut the western, lateral termination of the ancient orogen from ~32 Ma onward. This contrasted evolution leads to propose a palinspastic restoration taking in account important northward transport of the distal passive margin fragments (Briançonnais) involved in the accretionary prism before the formation of the Western Alps arc.

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1. Introduction

[2] The Alpine orogen resulted from the collision of the African and European continental margins of the Western Tethys ocean during Late Cretaceous to early Tertiary times. Most of the chain trends E-W, as a result of N-S Africa-Europe convergence [*Dewey et al.*, 1989; *Rosenbaum et al.*, 2002]. Although the orogen has been studied extensively, its structure, orogenic evolution and paleogeographic restoration are still debated [*Schmid et al.*, 2004; *Handy et al.*, 2010]. Since the work by *Argand* [1916], the origin of the arcuate shape of the western termination of the Alps has been a matter of debate, and different interpretations have been proposed or combined together. Existing models involve pre-Alpine paleogeographic inheritance and change in width of the Jurassic European margin [*Lemoine et al.*, 1989], the shape of the Adriatic indenter [*Tapponnier*, 1977; *Coward and Dietrich*, 1989], indenter-induced body forces causing variable transport/spreading directions, referred to as the radial outward model [*Platt et al.*, 1989b; *Rosenbaum and Lister*, 2005], rotation of the indenter and/or of the Penninic foreland [*Goguel*, 1963; *Boudon et al.*, 1976; *Ricou and Siddans*, 1986; *Vialon et al.*, 1989; *Laubscher*, 1988, 1991; *Choukroune et al.*, 1986; *Ménard*, 1988; *Thomas et al.*, 1999; *Collombet et al.*, 2002], and change in relative motion of the indenter [*Ramsay*, 1989; *Steck*, 1990; *Schmid and Kissling*, 2000; *Lickorish et al.*, 2002; *Ford et al.*, 2006].

[3] The tectonic transport directions in the Western Alps, measured by numerous researchers over the past 3 decades, show a radial pattern [*Malavieille et al.*, 1984; *Platt et al.*, 1989a; *Vialon et al.*, 1989; *Aubourg et al.*, 1999; *Sinclair*, 1997; *Lickorish et al.*, 2002]. Important shortening is observed in every part of the arc [*Schmid and Kissling*,

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2000; *Ford and Lickorish*, 2004; *Seno et al.*, 2005]. Any single-step restoration [i.e., *Sinclair*, 1997] comes up against a major problem of overlap in the core of the arc. The radial pattern appears to result from progressive deformation events from Eocene to Miocene, and includes ancient kinematic indicators which may have been rotated and/or overprinted during younger deformation stages, especially in the Internal Zones (Internal Nappes, Figure 1a) [*Collombet et al.*, 2002; *Rosenbaum and Lister*, 2005]. It is demonstrated that transport directions changed through time, both in the external and in the internal zones [e.g., *Lemoine*, 1972; *Merle and Brun*, 1981; *Choukroune et al.*, 1986; *Steck*, 1998; *Schmid and Kissling*, 2000; *Ceriani et al.*, 2001]. This can only be resolved through consideration of incremental displacements.

[4] The major outcropping feature which outlines the arc is a lithospheric thrust commonly called "Frontal Pennine Thrust" or "Pennine Thrust," a confusing name because some Penninic nappes are actually lying in its footwall (see section 2.2). It separates the External and Internal Zones and corresponds to at least 80 km offset of the Moho [*Guellec et al.*, 1990; *Lardeaux et al.*, 2006]. Crustal-scale cross sections in the western Alps are often drawn perpendicular to this structure, and the assumed transport direction is therefore typically also perpendicular to the map trace of the Pennine thrust. Thus, in different parts of the arc, this assumed transport direction may vary between NNW-directed and SW-directed. The restorations of these profiles usually do not take into account any lateral transport, which is a critical shortcoming in the case of radial profiles through the western Alpine arc (NNW-SSE profile [*Burkhard and Sommaruga*, 1998]; WNW-ESE profile [*Butler*, 1983]; NE-SW profiles [*Fry*, 1989; *Lickorish and Ford*, 1998; *Seno et al.*, 2005]). Moreover, there are important along-strike variations of structure [*Schmid et al.*, 2004], of metamorphism [*Bousquet et al.*, 2008] and of exhumation history [*Malusà et al.*, 2005].

[5] It can be demonstrated that the present-day expression of the "Pennine thrust" occurred quite recently in Alpine history and does not follow the earlier Alpine kinematics and geometry. It cuts across earlier thrusts, and older structures are transported within its hanging wall. Important displacements and rotations have been documented within the internal zones, which are superimposed on earlier Alpine structures [*Schmid and Kissling*, 2000; *Dèzes et al.*, 2004; *Thomas et al.*, 1999] thereby making internal Alpine geodynamic evolution difficult to restore precisely. In contrast, in the footwall of the "Pennine thrust" (in the External Zone) the displacements are of a lower order of magnitude [*Gratier et al.*, 1989], and rotations are moderate [*Aubourg et al.*, 1999]. It is thus possible to observe the interference between differently oriented shortening stages during the development of continental collision. This interference is a testimony of larger scale displacements and kinematic changes which occurred in the core of the chain.

[6] This paper presents new data concerning the deformation history and synsedimentary tectonics in the External Zone, and aims at integrating a large amount of published data from the western Alps, including the Internal Zones. It focuses on interference structures and variably directed nappe displacements which are found in the External Zone, within the western and southwestern parts of the arc, named Dauphiné and southern Subalpine domains, respectively. They involve, first, the Hercynian basement and the pre-orogenic sediments, and second, the Paleogene flexural basin recording the propagation of the Adria-Europe continental collision. In the former case, the preservation of the relationships between Hercynian basement and Mesozoic sediments makes it possible to evaluate the influence of both Hercynian and Tethyan inheritance during Alpine orogeny. A review of synorogenic sedimentation and of structural, metamorphic and chronological data available from the whole western and central Alps is incorporated, which provides an integrated framework for the investigated kinematic changes.

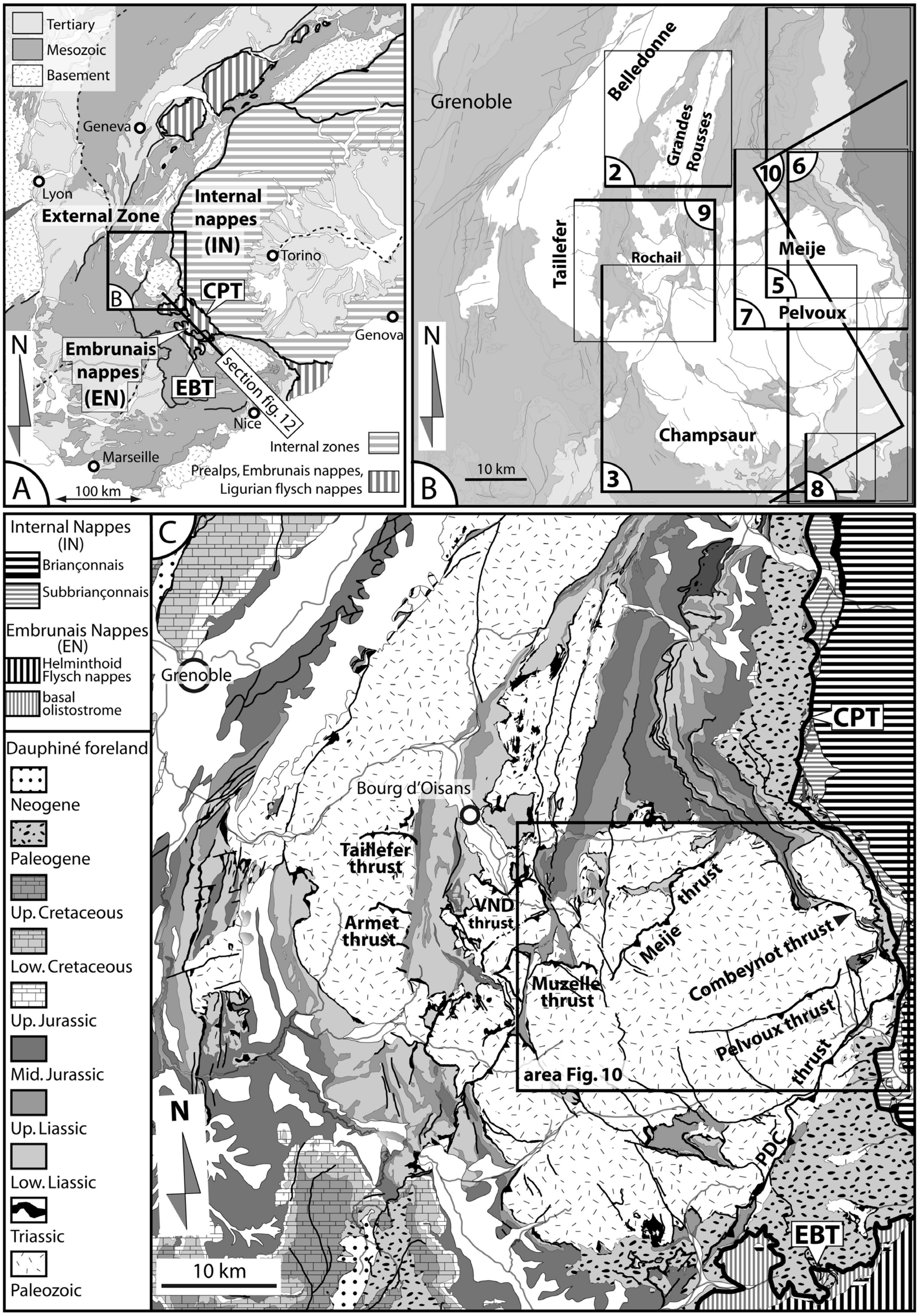
[7] One of the main issues is the occurrence of orogen-perpendicular (E-W or NE-SW) trending structures which indicate a significant component of N-S shortening, younger than the "Pyrenean-Provence" event sealed by the Paleogene flexural basin development, but older than the outward propagation of the Internal Nappes, which crosscut them. These transverse structures have previously been described in the literature [i.e., *Gidon*, 1979; *Bravard and Gidon*, 1979; *Bartoli et al.*, 1983; *Ford*, 1996], but they have been either underestimated or assigned to the Pyrenean-Provence shortening event, due to the Iberia-Europe convergence. It is proposed here that these structures are, in part, slightly younger (around Eocene-Oligocene boundary), and evolved in the footwall of an early Alpine nappe stack linked to the NW propagating Adria-Europe collision [see *Channell*, 1996].

2. Background

2.1. Stratigraphy and Pre-Alpine Setting

[8] The External Zone in Dauphiné (area B/C, Figure 1) is composed of elevated crystalline Hercynian basement massifs, surrounded by Tethyan sedimentary cover of Mesozoic age and more rarely of Cenozoic syn-orogenic sediments. The Hercynian basement massifs are composed of metamorphic and migmatitic rocks of Late Precambrian and Variscan age, intruded by late Variscan granites emplaced during early and late Carboniferous times. Erosional remnants of non-metamorphosed, latest Carboniferous coal measures and clastic sediments are classically regarded as belonging to the "basement" [e.g., *Guillot et al.*, 2009a].

[9] These massifs trend NE-SW from Mont-Blanc to southern Belledonne (Taillefer) and Grandes-Rousses, and NW-SE in the southernmost part of the Alpine arc (Argentera). The Pelvoux massif is located precisely at this sharp change in orientation (Figure 1a). The NE-SW trend is partly inherited from large-scale tilted fault blocks which formed part of the European passive margin of the Tethys ocean [*Barféty et al.*, 1979; *Barféty and Gidon*, 1980; *Lemoine et al.*, 1981, 1986]. This extensive zone of tilted fault blocks experienced approximately E-W shortening in the footwall of the Pennine thrust [*de Graciansky et al.*, 1988; *Coward et al.*, 1991; *Butler*, 1992; *Dumont et al.*, 2008]. Thus, important phases in their history can be illustrated using approximately E-W cross sections. By contrast, the Pelvoux massif has a sub-circular shape which requires 3D investigation and which has been interpreted in various ways, including the following models: (1) a late Hercynian granitic core [*Guerrot and Debon*, 2000], (2) a Tethyan


Tertiary
Mesozoic
Basement
Geneva
Lyon
External Zone
Internal nappes (IN)
Torino
CPT
Genova
Embrunais nappes (EN)
EBT
section fig. 12
Nice
Marseille
Internal zones
Prealps, Embrunais nappes, Ligurian flysch nappes
100 km
A
B
Grenoble
Belledonne
Grandes Rousses
Taillefer
Rochail
Meije
Pelvoux
Champsaur
10 km
2
3
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8
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10
C
Internal Nappes (IN)
Briançonnais
Subbriançonnais
Embrunais Nappes (EN)
Helminthoid Flysch nappes
basal olistostrome
Dauphiné foreland
Neogene
Paleogene
Up. Cretaceous
Low. Cretaceous
Up. Jurassic
Mid. Jurassic
Up. Liassic
Low. Liassic
Triassic
Paleozoic
Bourg d'Oisans
Taillefer thrust
Armet thrust
VND thrust
Meije thrust
Combeynot thrust
Muzelle thrust
Pelvoux thrust
thrust
area Fig. 10
PDC
N

Figure 1

submarine plateau based on the condensed Liassic facies which are found around it [*Lemoine et al.*, 1986; *Barféty*, 1988], and (3) a Tertiary pop-up structure in a tranpressive setting related to the Iberian plate convergence [*Ford*, 1996].

[10] A late Hercynian peneplanation process resulted in a flat and horizontal erosion surface over the whole study area between late Carboniferous and early Triassic times. It is manifested by a sharp unconformity at the base of the Dauphiné type Mesozoic sequence, characterized by the following formations:

[11] 1. Thin Triassic dolomites of Ladinian to Norian age show only minor thickness variation and peritidal facies implying that the whole area remained flat and horizontal until near end-Triassic times. There is no field evidence of large-scale block faulting, and subsidence rates were very low. The age of these dolomites range from late-middle Triassic to latest Triassic. The Triassic sequence thickens further S and SE, providing potential detachment layers within evaporitic layers [*Courel et al.*, 1984].

[12] 2. Thin but widespread flood basalts are indicative of intracontinental rifting [*Laurent*, 1992]. This short volcanic event marks the onset of Tethyan rifting in the Pelvoux massif area [*Dumont*, 1998].

[13] 3. Thin, lowermost Liassic transgressive platform carbonates are overlain by thick Liassic to Middle Jurassic hemipelagic marls and limestones. These latter formations, which were deposited during the Tethyan rifting, show important thickness and facies changes together with angular unconformities [*Barféty and Gidon*, 1983; *Barféty*, 1988; *Lemoine et al.*, 1986; *Dumont*, 1998]. Differential subsidence is evident during the Sinemurian [*Chevalier et al.*, 2003], with a resultant major impact on the distribution of sedimentary wedges, thereby enabling the identification of the main rift structures [*Lemoine et al.*, 1986; *Dumont et al.*, 2008].

[14] 4. Post-rift late Jurassic to early Cretaceous pelagic carbonate formations are rarely preserved in the Dauphiné massifs, but there is locally observed unconformity characterized by Tithonian limestones overlying directly the Hercynian basement [*Barféty and Gidon*, 1983]. The post-rift cover is widespread further to the south, changing from basinal facies in the Vocontian trough to platform deposits in the area between Provence and the Maritime Alps. The platform margin trended E-W across the present location of the Argentera basement massif [*Enay et al.*, 1984], and it is crosscut and displaced by Alpine thrusts.

[15] 5. The overlying Upper Cretaceous formations are preserved only in the Subalpine massifs surrounding the Dauphiné (Chartreuse, Vercors, Devoluy and Southern Subalpine domain). They record the earliest, north-directed compressional deformation due to the motion of the Iberian block (pre-Senonian folding in Devoluy [*Meckel et al.*, 1996; *Michard et al.*, 2010]).

[16] 6. The Paleogene sequence which caps the Dauphiné and Subalpine series occurs in the proximal footwall of the Internal Nappes. It includes middle to late Eocene platform limestones [*Pairis*, 1988], hemipelagic marls and thick turbiditic sandstones/shales alternations, named "Grès d'Annot" or "Grès du Champsaur" [*Ravenne et al.*, 1987; *Waibel*, 1990] and "Flysch des Aiguilles d'Arves" or "Grès de Taveyanne" further north. The Paleogene sequence overlies a sharp continental erosional surface showing a downward increasing truncation of the Mesozoic sequence from the southern Subalpine to the Dauphiné areas, indicative of an important pre-Priabonian (Mid Eocene) exhumation of the Pelvoux massif [*Gupta and Allen*, 2000]. South-directed compressional structures are associated with this event in the Southern Pelvoux region [*Gidon*, 1979; *Ford*, 1996]. The Paleogene subsidence is due to flexural bending of the European foreland underneath the propagating Apulian wedge [*Sinclair*, 1997]. The Paleogene sediments are capped by a characteristic formation containing olistostromes over much of the Western Alpine arc ("Schistes à blocs" [*Kerckhove*, 1964]) and the sedimentation is interrupted by the gravity-driven emplacement of the first "exotic" nappes in the basinal setting [*Kerckhove*, 1969].

2.2. Compressional Structural Setting

[17] In the main area of interest, the early compressional deformation stages pre-date the Alpine collision, because of their late Cretaceous to Eocene, pre-Priabonian ages, and considering the Priabonian age of the oldest deposits in the Alpine flexural basin. These N-S shortening phases events are usually assigned to sinistral migration of the Iberian plate [*Meckel et al.*, 1996; *Ford*, 1996] associated with the local development of large-scale gravity sliding in a submarine setting [*Michard et al.*, 2010].

[18] The Alpine wedge in the study area is classically regarded as propagating toward the west to southwest, crosscutting the previous contractional structures. However, it has been noticed that the modern arcuate chain does not feature the early stages of Alpine collision [*Ford et al.*, 2006; *Dumont et al.*, 2008]. The earliest Alpine nappes are interpreted to have been gravitationally emplaced from the SE in a submarine setting [*Kerckhove et al.*, 1978]. These nappes are composed of deep-water sediments which were possibly deposited on an oceanic crust during the late Cretaceous. They have been transported in an approximately NW direction across the distal portion of the European passive margin (represented partly by the Briançonnais zone), and subsequently further across the more proximal portion of the passive margin during latest Eocene to earliest Oligocene time, following a different transport direction [*Merle and Brun*, 1981; *Ford et al.*, 2006]. This early Alpine nappe stack is named "Embrunais Nappes" in the study area (EN, Figure 1), and the basal thrust is called "EBT." This nappe stack corresponds to the "Prealpine nappes" in the

Figure 1. (a) Overall map of the Western Alps and foreland. EBT: Embrunais Basal Thrust; CPT: Crustal Pennine Thrust. (b) Location of block diagrams of Figures 2 to 10. Hercynian basement massifs in white, Meso-Cenozoic sedimentary cover and nappes in gray. (c) Geological map of the Dauphiné area: 1 to 10; External zone (Dauphiné): 1: Hercynian basement; 2: Triassic; 3: lower Liassic; 4: upper Liassic; 5: middle Jurassic; 6: upper Jurassic; 7: lower Cretaceous; 8: upper Cretaceous. 9: Paleogene; 10: Neogene. 11–12: Internal Nappes (IN): 11: lower Briançonnais nappes ("Subbriançonnais"); 12: Briançonnais nappes. 13–14: Embrunais nappes (EN): 13: olistostrome ("Schistes à blocs"); 14: Helminthoid flysch nappes.

northern part of the arc. While early motions are apparently dominantly to the NW [*Merle and Brun*, 1981; *Ford et al.*, 2006], it is observed that the later stages of thrust system propagation (which involved outerward translation of the Internal Nappes (IN, Figure 1) over the Dauphiné-Helvetic foreland) were more radially directed. The main associated structure is a lithosphere-scale thrust inappropriately termed the "Pennine thrust" because some earlier nappes of Penninic origin are lying in its footwall (the Embrunais-Ubaye nappes after *Kerckhove* [1969], simply named "Embrunais Nappes" in this paper) and in its hanging wall also [*Gidon*, 1955]. Following *Sue and Tricart* [2003], we propose to name it the "Crustal Pennine Thrust" or CPT (Figure 1), which is the present limit between the non-metamorphic foreland (including the early Embrunais Nappes) and the metamorphic, Internal Nappes stack. The mature collision stage corresponds to the initiation of lateral extrusion in the Western Alpine arc [*Dumont et al.*, 2008], which started during early Oligocene [*Simon-Labric et al.*, 2009]. The Pelvoux external basement massif is thus located in the footwall of these two successively emplaced nappe systems (EBT and CPT) which propagated in different directions.

[19] To conclude, orogen-perpendicular profiles commonly found in the literature are improperly oriented to understand the early Alpine transport directions in the southern part of the arc. The relicts of the early contraction are better crosscut by orogen-parallel sections (SE-NW to N-S) both in the internal zones [*Tricart and Schwartz*, 2006] and in the external foreland as shown below.

3. Regional Structure and Deformation History of the Dauphiné Basement Massifs

3.1. Hercynian and Tethyan Inheritance

[20] The structure of the External Crystalline basement massifs in the Western Alps was strongly influenced by a N30° fault trend extending from the Bohemian massif to Corsica during Permo-Carboniferous times, the so-called External Crystalline Shear Zone [*Matte*, 2001; *Corsini and Rolland*, 2009; *Guillot and Ménot*, 2009]. This overall trend includes local N-S dextral strike-slip faults [*Guillot et al.*, 2009a]. The reorientation of the Hercynian grain can be used as a post Permian deformation marker.

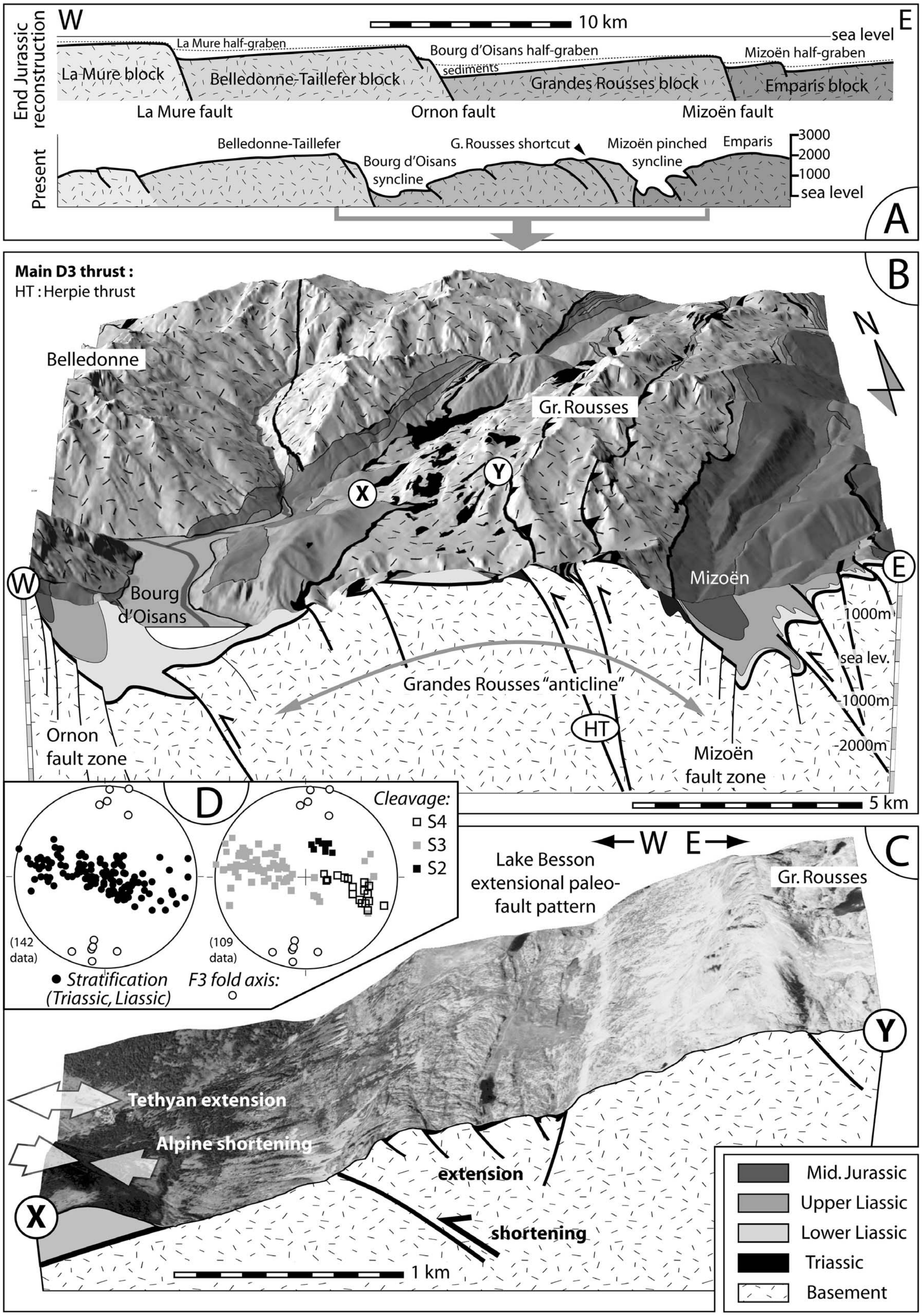
[21] N-S oriented tilted blocks are well known in the Bourg d'Oisans region (Figure 1c), to the NW of the Pelvoux area [*Lemoine et al.*, 1981, 1986]. Their orientation is subparallel to the Hercynian grain in this area (~N-S), but the distribution of Liassic depocenters suggests that Tethyan syn-rift extension was oblique to it (NW-SE [*Lemoine et al.*, 1989; *Dumont et al.*, 2008]). Alpine inversion consists mainly of buttressing in the hanging wall of master rift faults and shortcuts in their footwall (Figure 2a). Basement shortening and folding increase eastward, toward the Crustal Pennine Thrust. Large-scale structures such as the Grandes Rousses massif are basement anticlines superimposed on 10 km-wide tilted blocks (Figure 2b): the western and eastern limbs of the Grandes Rousses basement anticline preserve an expanded and a highly condensed syn-rift sequences, respectively [*Dumont et al.*, 2008]. Small-scale Tethyan rift structures were passively uplifted and incorporated in the Alpine folding, as shown by smaller-scale structures (Figures 2c and 2d). Thus, in this area, most of the extensional and compressional deformation, which were approximately coaxial, can be appropriately represented along approximately E-W cross sections.

[22] However, this relatively simple inversion setting occurs over a quite restricted part of the Dauphiné external massifs. Elsewhere around the Pelvoux massif, the Hercynian grain, the Tethyan structures and several shortening episodes have various orientations and understanding their interaction requires 3D analysis. For example, the trend of Hercynian grain rotates to NW-SE in southern Pelvoux and in the Argentera basement and was probably reactivated as strike-slip faults by the Jurassic extension (Lac du Vallon fault [*Barféty and Gidon*, 1983] and Morges fault [*Lazarre et al.*, 1996; *Dardeau*, 1983]). The entire central Pelvoux area is cored by a relatively homogeneous late Hercynian granite [*Guerrot and Debon*, 2000] with little evidence of important variations in the syn-rift series around the massif [*Barféty*, 1988]. However, the condensation and locally submarine erosion of syn-rift sediments [*Barféty et al.*, 1986] suggest that the Pelvoux massif was an extensive marginal swell before the initiation of Alpine collision.

3.2. Pre-Priabonian Structures (D1)

[23] High-angle basement thrusts sealed by Priabonian sediments are well known in the south and SW Pelvoux area [*Gidon et al.*, 1980; *Ford*, 1996]. The kinematic indicators in the footwall Mesozoic sediments consistently show a S-SW transport direction (sites 5 to 7, Figure 3 and field example Figure 4) with increasing eastward plunge of the fold axis (site 7). Further north, another set of basement thrusts shows similar kinematic data (Figures 3 and 5; S-SW to SW-directed, sites 1 to 4) but are not sealed by the Priabonian, except at the southeastern termination (site 8). The associated fold axes were clearly involved in further E-W shortening because on both sides of the Pelvoux massif they are tilted in opposite directions (Figure 3, inset C). We propose that this set of structures was also produced by pre-Priabonian deformation. This compressional event caused an important exhumation of the whole southern part of the massif with complete removal of the Mesozoic stratigraphic section by continental erosion. This event has no link with the pre-Senonian Devoluy tectonic phase which deformed the Mesozoic cover further west in the deep marine environment [*Michard et al.*, 2010] as it occurred soon before the Pria-

Figure 2. Tethyan inheritance in north Dauphiné area: (a) restored and present cross-sections of the Jurassic tilted blocks pattern in northern Dauphiné. (b) Block diagram of the large-scale Grandes Rousses basement fold, superimposed on a first-order tilted block. (c and d) Sub-parallel Tethyan extension and Alpine shortening on the west slope of the Grandes Rousses block (small-scale, Jurassic extensional pattern of the Lakes Besson area). Despite several contractional deformations are observed (3 superimposed cleavages), the main folds are trending parallel to the Jurassic faults, because both Jurassic extension and Alpine shortening were guided by the Hercynian structures [*Dumont et al.*, 2008]. (d) Wulff projection, lower hemisphere.



W
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Belledonne-Taillefer block
Grandes Rousses block
Emparis block
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S4
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(142 data)
(109 data)
Stratification (Triassic, Liassic)
F3 fold axis:
C
W E
Lake Besson extensional paleo-fault pattern
Gr. Rousses
Tethyan extension
Alpine shortening
extension
shortening
1 km
Mid. Jurassic
Upper Liassic
Lower Liassic
Triassic
Basement

Figure 2

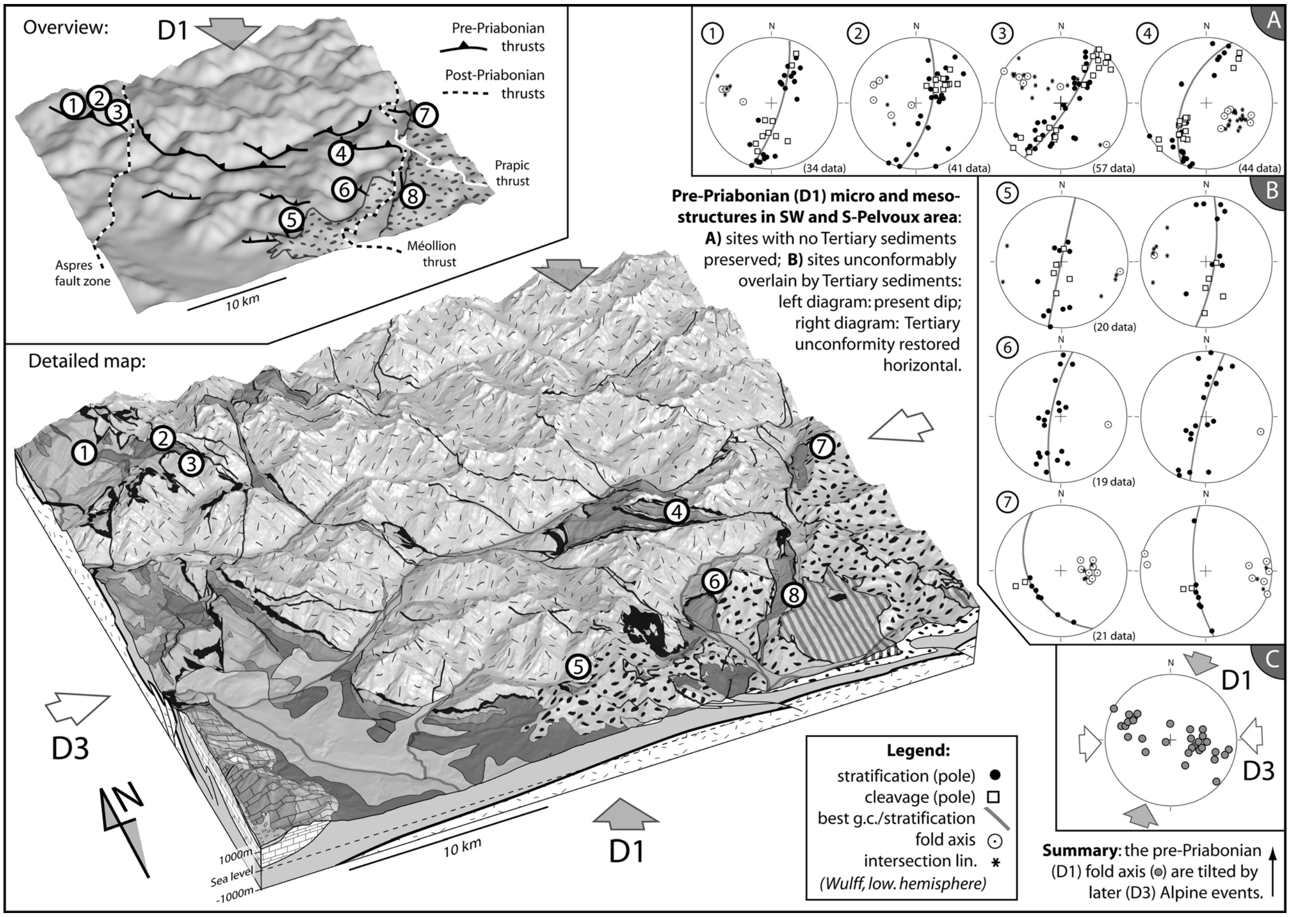

Figure 3. Pre-Priabonian contractional imprint (deformation D1) in the SW part of the Dauphiné cristalline massifs (location Figure 1b; same mapping legend as Figure 2): Some SSW-verging thrusts and exhumed basement are sealed by Priabonian sediments (sites 5, 6, 7, 8 and inset B). Some others are not, but display similar structures and deformation history (sites 1, 2, 3, 4 and inset A). The Sirac thrust (site 4) is related with a pre-Priabonian thrust at site 8. Large-scale E-W tilting of fold axes (inset C) show that these contractional structures have been overprinted by Alpine E-W shortening. Location of the sites: (1) south slopes of Pointe de Confolant, SW Rochail massif; (2) Combe Guyon-Lac Labarre; (3) upper Vallon de Valsenestre, south slopes of Brèche du Lauvitel; (4) Mourière, SE of Refuge de Vallonpierre, west of Sirac peak; (5) le Vaccivier, upper Muande valley; (6) le Vallon, west slopes of Cedera massif, east of Drac Blanc valley; (7); le Clot Agnel, upper Vallon de la Selle; and (8) west slopes of Sommet Drouvet, near Orcières-Merlette ski resort.

bonian transgression onlapped a rugged topography and probably active reliefs [*Gupta and Allen*, 2000]. The southern Subalpine domain also developed a large wavelength uplift with NW-ward truncation from the Upper Cretaceous down to Jurassic sequences underneath the Eocene transgression.

[24] This pre-Priabonian deformation episode cannot correspond to forebulge uplift preceding the flexural subsidence, because of the occurrence of basement thrusts and recumbent folds below the basin floor. It is instead regarded as a distant effect of the Iberian plate motion [*Ford*, 1996, and references therein]. The southward to southwestward vergence of the basement thrusts, a feature restricted to the southern Pelvoux area, may indicate an incipient structural inversion at the northern edge of the Vocontian basin, whose thick Mesozoic series are found to the south of the massif. Further west (Subalpine massifs), neither basement uplift nor south-vergent thrusting are found, which implies the occurrence of a transcurrent fault system as proposed by *Ford* [1996]. We observe that one of these pre-Priabonian trends re-activates some minor early synrift Tethyan faults (location 1, Figure 3) but does not seem to crosscut the major Ornon fault (Figure 2). We thus consider that the major, NS-oriented Tethyan boundary faults located to the west of the Pelvoux massif acted as transcurrent boundaries during the Eocene.

[25] To the north of the Pelvoux massif, SSE-ward truncation of Jurassic beds down to the basement occurs [*Barbier et al.*, 1973]. In spite of strong further deformation by D2 and D3 folds and thrusts, the pre-Priabonian erosional unconformity rests on gently folded middle-upper Jurassic beds (a, Figure 5), then on Liassic to Triassic beds (b, c) with <10°NW-ward pre-Priabonian tilt (c), and finally on the basement (d). The base of Eocene sediments (coarse fluviatile conglomerates, “Flysch des Aiguilles d’Arves”

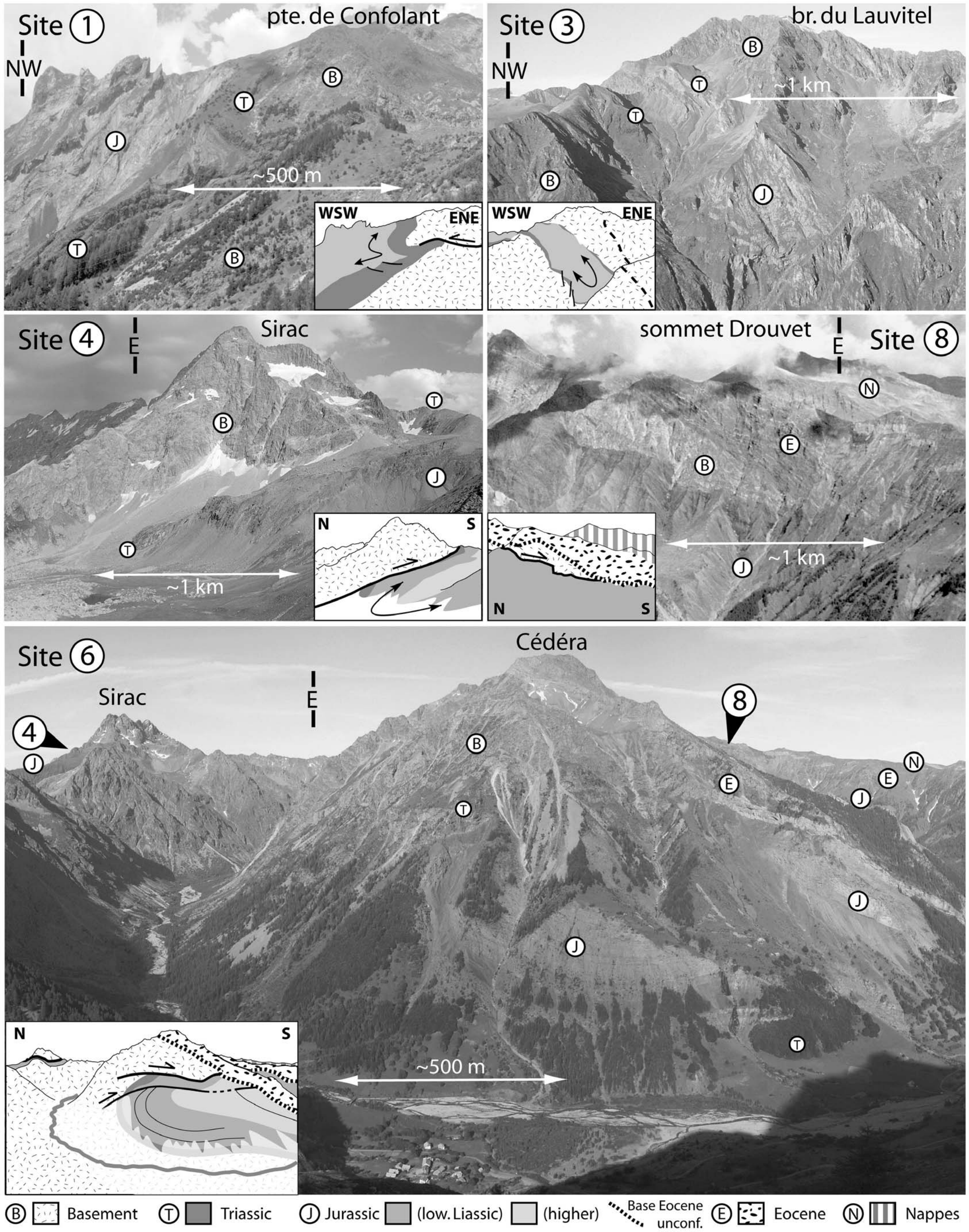

Figure 4. Field examples of pre-Priabonian structures, either sealed by Eocene (Priabonian) sediments (sites 6 and 8) or not (sites 1, 3, and 4). Location of sites is given on Figure 3.

formation) onlaps the erosional surface southward and is partly sourced by the Pelvoux basement [*Ivaldi*, 1987]. This pre-Priabonian, southward pinch-out unconformity is crosscut by NW-directed thrusts locally involving the basement (section 3.3), in the footwall of which high-angle reverse basement faults (Figure 5) have been attributed to the pre-Priabonian event based on their top-to-the-north direction [i.e., *Bravard and Gidon*, 1979; *Ford*, 1996; *Sue et al.*, 1998], an interpretation which has been challenged by *Dumont et al.* [2008].

3.3. Early Alpine, North to Northwest-Vergent Transport (D2)

[26] Considering the N-S convergent kinematics of the Central and Eastern Alps and the important northward displacement of the Alpine orogenic wedge postulated during late Eocene times [*Froitzheim et al.*, 1994; *Schmid and Kissling*, 2000; *Dèzes et al.*, 2004], a major sinistral-oblique accommodation zone is predicted at the western end of the orogen. According to *Dèzes et al.* [2004], the External

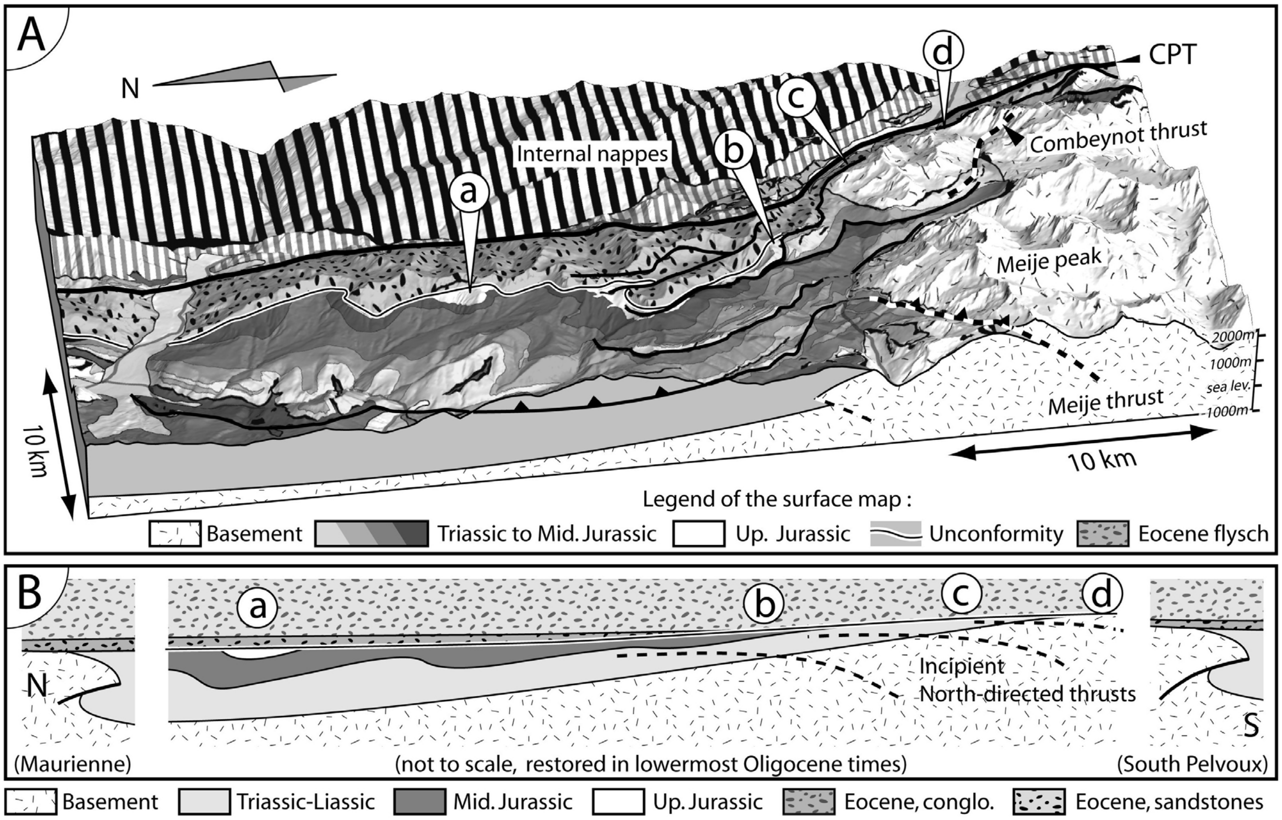

Figure 5. Restoration of pre-Priabonian (D1) structures in NE Dauphiné area: (a) Present block diagram, view from the WNW. (b) Restored N-S section before deformation D2: the Eocene sediments are onlapping a low-angle erosional unconformity surface southward, from folded Jurassic marls (site a) toward exhumed basement of E Pelvoux massif (site d). This unconformity is consistent with the pre-Priabonian south-directed thrusts found in south Pelvoux area (Figures 3 and 4). This unconformity has been further truncated and deformed by NW- directed (D2) and west-directed (D3) folds and thrusts.

western Alps have not been involved in this early Alpine collisional episode, but the Pelvoux massif area does show evidence for deformation at this age.

[27] The southern and eastern sides of the Pelvoux massif show evidence of important northward or NW-ward displacements, both within the basement and near the basement-cover interface. The main thrust, named by *Vernet* [1966] the "Perron des Claux" thrust, can be followed laterally over more than 30 km (Figure 6). It is located close to the top of the basement, either duplicating Mesozoic and Tertiary cover sequences in the Orcières area (site 8, Figure 6), or detaching thin basement slices in the eastern Pelvoux region (sites 9 to 11, Figure 6). Further north, it probably connects to the "Madeleine" thrust which duplicates the Eocene sequence over the Combeynot basement unit (site 12, Figure 6) [*Barbier et al.*, 1973]. The deformation in its footwall at localities 8 and 11 indicates a NW-ward transport, although they are severely overprinted by top-to-the-west shearing in the footwall of the Crustal Pennine Thrust (site 11 [*Pêcher et al.*, 1992; *Butler*, 1992]). The ability of the Perron des Claux thrust to propagate northward at a regional scale from the Meso-Cenozoic cover to the top of Hercynian basement in the eastern Pelvoux area (Figure 6, block diagram) demonstrates that the latter had been previously uplifted, namely by pre-Priabonian shortening. This thrust is in turn deformed during younger Alpine events as shown by (1) long wavelength folding clearly visible in Figure 6, (2) the enhancement of eastward dip caused by differential uplift of the Pelvoux massif with respect to Internal Nappes during the Neogene [*Tricart et al.*, 2001] and (3) the offset of the thrust by several late orogenic NE-SW dextral strike-slip faults with moderate displacements.

[28] In the footwall of the Perron des Claux thrust, the basement is affected by several north- to northwest-directed high-angle reverse faults: the Pelvoux thrust (PeT, Figure 6) causes the uplift of the highest basement peak (the Pelvoux peak) in its hanging wall, and reaches the basement-cover interface producing N-directed imbricates in the lower Mesozoic sediments [*Pêcher et al.*, 1992]. The Combeynot thrust (CoT) and Meije thrust (MeT) transport folded basement over the Jurassic cover further north. These structures show structural evidence of older north- to northwest-ward transport directions: small-scale reverse limb, ENE-WSW trending folds in the footwall of CoT at Col d'Arsine, which are overprinted by westward shear, and top-to-the NW shear bands at the base of the Combeynot basement thrust sheet which yielded a lowermost Oligocene $^{40}Ar/^{39}Ar$ age [*Authemayou*, 2002; *Heymes*, 2004; *Simon-Labric et al.*, 2009]. At a larger scale, the Meije thrust climbs section in its footwall toward the north, despite an

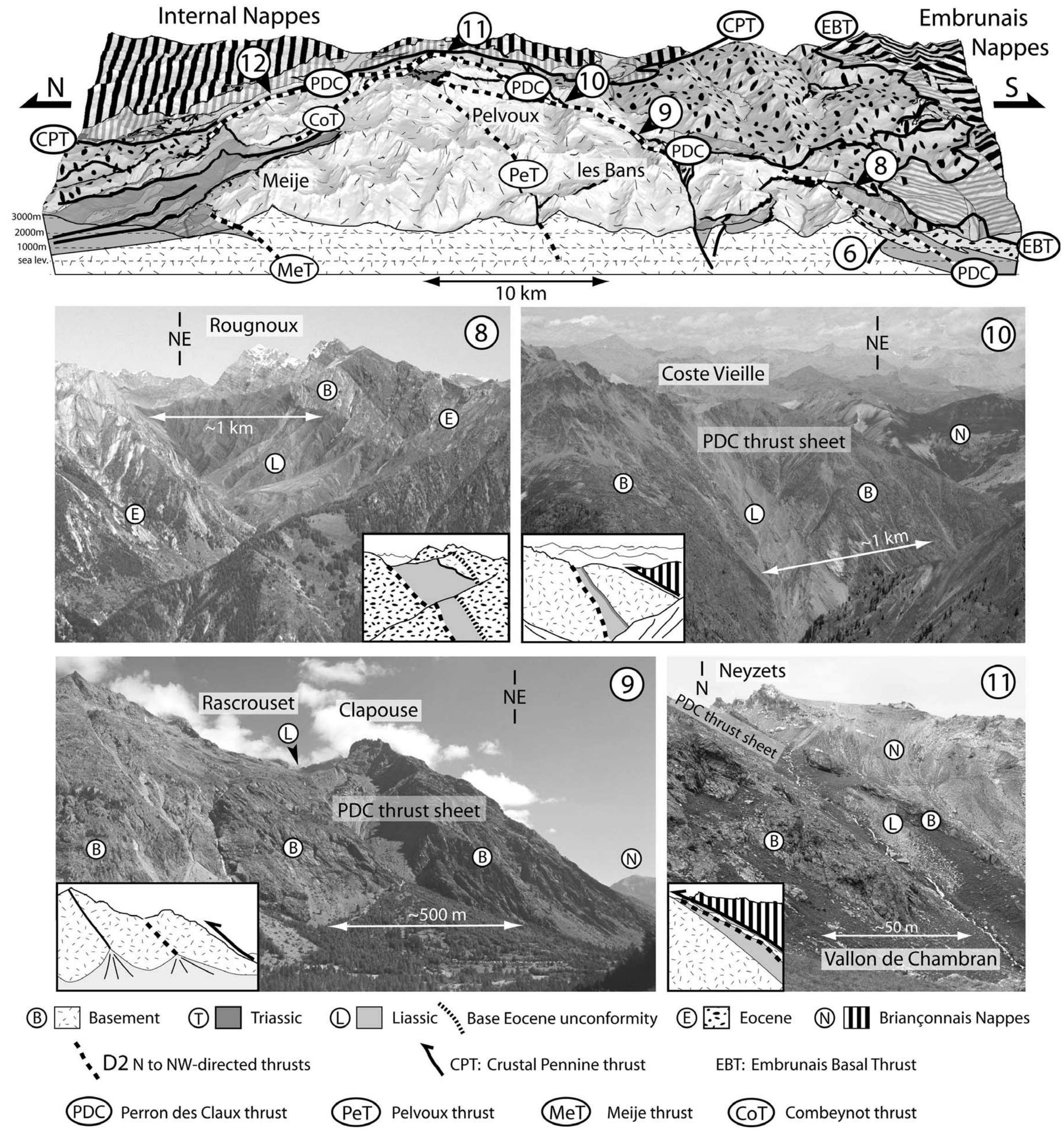

Figure 6. Post-Priabonian, north- to northwest-directed Alpine structures (deformation D2) in east and SE Pelvoux areas: basement thickening in the core of the massif, previously exhumed during D1 (Figure 5), is enhanced by D2. It occurred in the footwall of the Embrunais Nappes, and it developed a large basement slice at the eastern border of the Pelvoux (Perron des Claux, PDC thrust sheet; sites 9 to 11). This deformation pre-dates the westward thrusting of Internal Nappes (deformation D3) whose basal thrust (CPT) truncates the basement culmination. Site 11 is located close to this culmination: the Internal Nappes are only <100 m above the Pelvoux basement, and very strong westward shear overprints the Perron des Claux thrust sheet in their footwall. Location of field photographs of the Perron des Claux thrust sheet: (8) col de Méollion and Sommet Drouvet, north of Orcières; (9) northern side of Les Bans valley (Onde river); (10) northern side of Ailefroide valley, between Ailefroide and Pelvoux villages; (11) upper Vallon de Chambran, SE of Rochers de l'Yret; and (12) NE slopes of the Combeynot massif (Rochers de la Madeleine).

apparent NE-ward dip which is due to further tilt, so that the main structures are best viewed using east-plunging perspective maps (Figures 7a and 7d). The hanging wall basement of the Meije and Combeynot thrusts include large wavelength ramp anticlines involving the granitic core, the gneissic envelope and the Triassic-lower Liassic sedimentary cover (Figures 7b and 7c). The E-W trend of these large-scale basement anticlines precludes interpreting these thrusts as lateral ramps of westward propagating basement thrust sheets.

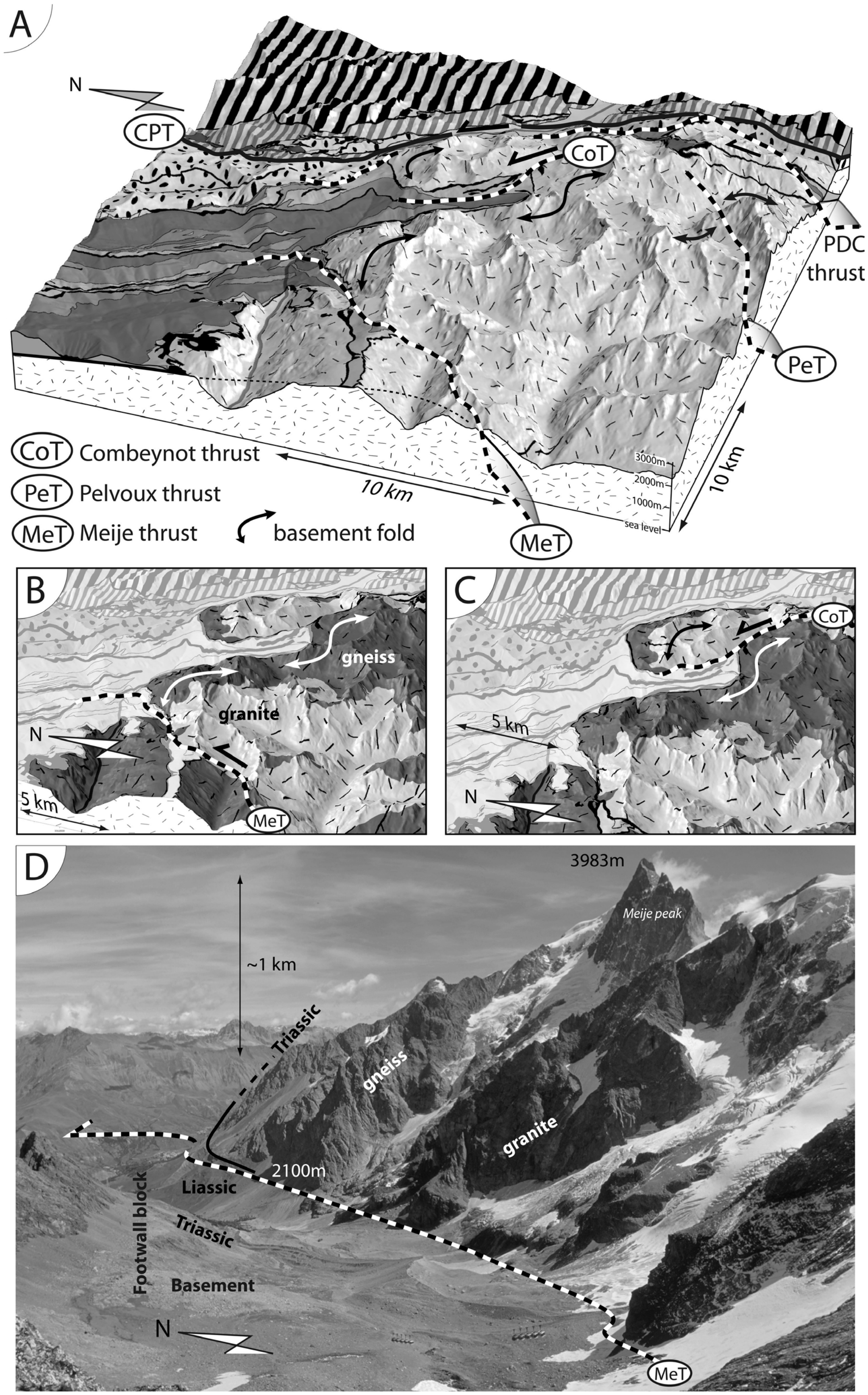
A
N
CPT
CoT
PDC thrust
PeT
CoT Combeynot thrust
PeT Pelvoux thrust
MeT Meije thrust
basement fold
10 km
10 km
3000m
2000m
1000m
sea level
MeT
B
gneiss
granite
N
5 km
MeT
C
CoT
5 km
N
D
3983m
Meije peak
~1 km
Triassic
gneiss
granite
2100m
Liassic
Triassic
Footwall block
Basement
N
MeT

Figure 7

[29] In the hanging wall of the Perron des Claux thrust, the duplicated Meso-Cenozoic sequence is overlain by a thick Tertiary olistostrome (formation "complexe d'Orcières" [*Debelmas et al.*, 1980]) and above by the Embrunais Basal Thrust, which forms the basal thrust of the non-metamorphic Embrunais Nappes stack. The southwestern continuation of the Perron des Claux thrust, corresponding to the Soleil-Bœuf and Palastre slices located to the west of Orcières, show evidence of early NW-directed transport directions [*Gidon and Pairis*, 1980]. Both in the latter locality and in the northern continuation of the Perron des Claux thrust (Madeleine and Côte Plaine thrust sheets [*Bravard and Gidon*, 1979]) thrusting occurred very soon after the final deposition of the late Eocene flysch as evidenced by soft-sediment deformation [*Butler and McCaffrey*, 2004]. Consistently, the hanging wall Eocene sequence of the Perron des Claux thrust suffered N to NW recumbent isoclinal folding sealed by the olistostrome south of Orcières [*Kerckhove et al.*, 1978; *Debelmas et al.*, 1980]. This suggests that the initial emplacement of the Embrunais Nappes, which occurred in a shallow setting during the lowermost Oligocene, was directed NW-ward and not SW-ward as postulated by *Kerckhove* [1969] or *Bürgisser and Ford* [1998]. The thickness of the Embrunais Nappes stack ranged between 4 and 8 km [*Labaume et al.*, 2008] and is likely to have covered the Pelvoux region (Champsaur [*Waibel*, 1990]). Thus, we propose to associate the D2 deformation episode having affected the Pelvoux basement and Mesozoic cover with the Embrunais nappes stacking.

3.4. Main Alpine, West-Directed Stacking (D3) and D3/D2 Interference

[30] The dominantly westward directed shear in the footwall of the Crustal Pennine Thrust at the eastern edge of the Pelvoux massif is well documented [i.e., *Tricart*, 1980; *Beach*, 1981; *Butler*, 1992; *Bürgisser and Ford*, 1998]. Approximately 30° diverging transport directions on both sides of the Pelvoux culmination [*Gamond*, 1980; *Tricart*, 1980], drag folding on its southeastern slope [*Bürgisser and Ford*, 1998] and enhanced shear on top of it [*Butler*, 1992] clearly demonstrate the occurrence of an important basement uplift prior to the westward transport of Internal Nappes on the Crustal Pennine Thrust. This uplift is due to cumulative effects of D1 and D2 basement thickening. The D3/D2 interaction is found in the upper footwall of the Crustal Pennine Thrust to the north of the Pelvoux, with a change in transport directions from N-NW to W-NW or west [*Bravard*, 1982; *Ceriani et al.*, 2001].

[31] To the SE of the Pelvoux massif, the D2 northwestward recumbent fold involving the late Eocene flysch is overprinted by D3 westward folding (Figure 8), together with the olistostrome and the Embrunais Nappes. Antiformal folds are developed both within the reverse limb and within the normal way-up section in the footwall of the Prapic thrust, which is kinematically linked with the WSW-ward propagation of shortening in front of the Crustal Pennine Thrust [*Bürgisser and Ford*, 1998]. To the NW of the Pelvoux, complicated 3D structures are due to a perpendicular change in shortening orientation, from approximately N-S (D2) which generated a set of north-directed high-angle basement thrusts to approximately E-W (D3) which deformed these thrusts with strike-slip reactivation [*Dumont et al.*, 2008] (Figure 9). In this area, D3 deformation produced buttressing and shortcutting along the elevated parts of the Jurassic fault blocks.

[32] The D3/D2 interference pattern can also be observed in the core of the Pelvoux massif: based on the complete erosion of the basement-cover interface in the central part, the boundary between the granitic core and metamorphic envelopes provides an alternative reference surface. As shown in Figure 10, this surface is deformed with similar geometry to the peripheral basement-cover interface, thereby precluding any Hercynian origin for this structure. The Meije dome is thus a result of N-S "arching" in the hanging wall of the Meije thrust (D2, Figure 7) and E-W arching in the footwall of the Crustal Pennine Thrust (D3). This dome is effectively a smaller scale version of the subcircular Pelvoux massif.

4. Syn-orogenic Basins

4.1. Foreland Basin Propagation and Orogen Migration During the Eocene

[33] Most of the European foreland, corresponding previously to the proximal part of the Tethyan margin, emerged before the Eocene [*Pairis et al.*, 1984], due to the Pyrenean-Provence orogenesis (deformation D1). Subsequently, the propagation of the Alpine Paleogene flexural basin is marked by a sharp transgressive surface, locally unconformable, followed by a rapid deepening. Due to flexural subsidence, the facies grade upward from platform limestones to hemipelagic foraminiferal marls and thick turbiditic sandstone series, named "Grès d'Annot," "Grès du Champsaur," "Flysch des Aiguilles d'Arves" and "Grès de Taveyannaz" from south to north. A compilation of stratigraphic data (Figure 11) clearly shows the diachroneity of this transgressive sequence over the whole Eocene time span. Coarsening upward, time equivalent flysch sedimentation occurred without emersion on more distal domains of the Tethyan margin, now included in the Penninic nappe stack (Briançonnais units), and erosional unconformities

Figure 7. Post-Priabonian, north- to NW-directed basement-involved thrusts and associated basement folds (deformation D2) in NE Pelvoux area. (a) The Meije (MeT) and Combeynot (CoT) basement thrusts are climbing section northward, reaching the Mesozoic sequence. The northern termination of the Perron des Claux thrust sheet (above PDC thrust) overlies the Combeynot basement. All are overprinted by top-to-the W shear in the near footwall of the Crustal Pennine Thrust (CPT; deformation D3). Same mapping legend as Figure 1. (b and c) Eastward perspective views of the Meije and Combeynot basement hanging walls, showing the ramp anticlines with folded granite-gneiss boundary. Both are plunging eastward due to further D3 tilting. Same mapping legend as Figure 1. (d) The Meije thrust from the top of the Glaciers de La Meije cableway. Note the steep northward dip of granite-gneiss and gneiss-Triassic boundaries in the hanging wall ramp anticline.

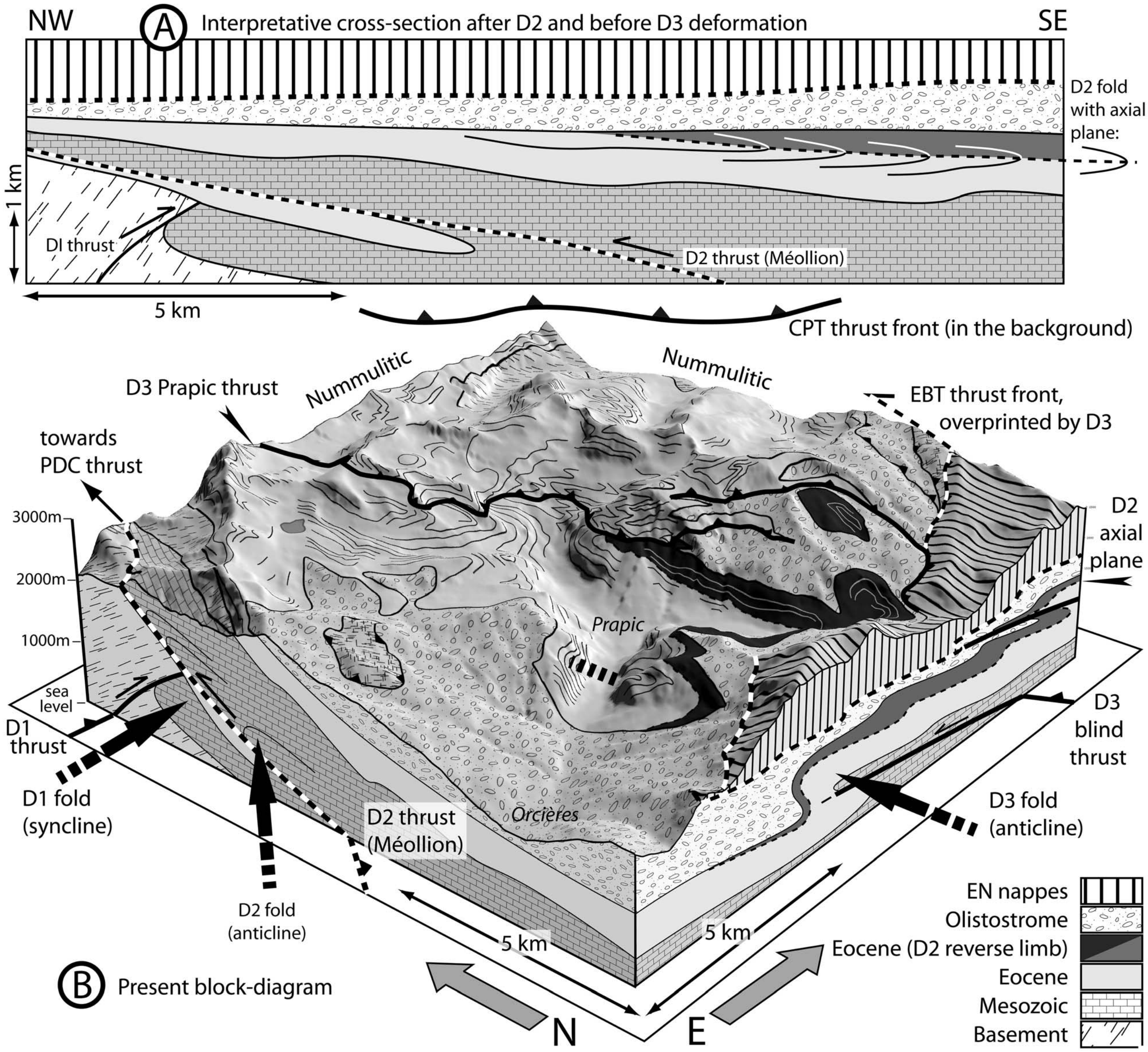

Figure 8. Interferences between D1, D2 and D3 fold-and-thrusts in the Orcières region (SE Pelvoux). (a) Section restored before D3 deformation: the Eocene series is duplicated by a NW-directed D2 thrust and affected by isoclinal folding with a kilometric-scale reverse limb in the footwall of the Embrunais Nappes (EN). (b) Block diagram showing that this reverse limb is involved in D3 folding (Prapic fold) beneath the top-to-the WSW Prapic thrust, which in turn occurred in the footwall of the Crustal Pennine Thrust (CPT).

originate at the transition between these and the proximal margin (Subbriançonnais domain).

[34] An age gradient occurs from south (or SE) to north (or NW) both in the strongly shortened south Helvetic to Helvetic realm, and in the more completely preserved foreland of the southern part of the western Alpine arc (Maritime Alps toward Subalpine domain, or Provence toward Dauphiné). North- to northwest-ward coastal migration in the southern Subalpine domain [*Kerckhove*, 1969] and in the Helvetic realm [*Kempf and Pfiffner*, 2004], sediment supply from the south and northward or NW-ward sedimentary transport directions in the southern Subalpine area [*Ravenne et al.*, 1987; *Callec*, 2001] are in agreement with the direction of propagation. Consistent with the proposition of *Ford et al.* [2006], the distribution of the Eocene flexural basin has been heavily distorted by the younger development of the arc. Based on the work by *Schmid and Kissling* [2000], palinspastic reconstruction, the NW-ward propagation rate of the Paleogene flexural basin can be estimated at about 1 cm/yr (similar estimations from *Sinclair* [1997], *Stampfli et al.* [2002], *Ford and Lickorish* [2004]), which corresponds to both the Africa-Europe convergence rate after *Rosenbaum et al.* [2002] and the subduction rate of the distal parts of the European margin at that time [*Berger and Bousquet*, 2008]. This suggests that during the Eocene, the Apulian orogenic wedge moved

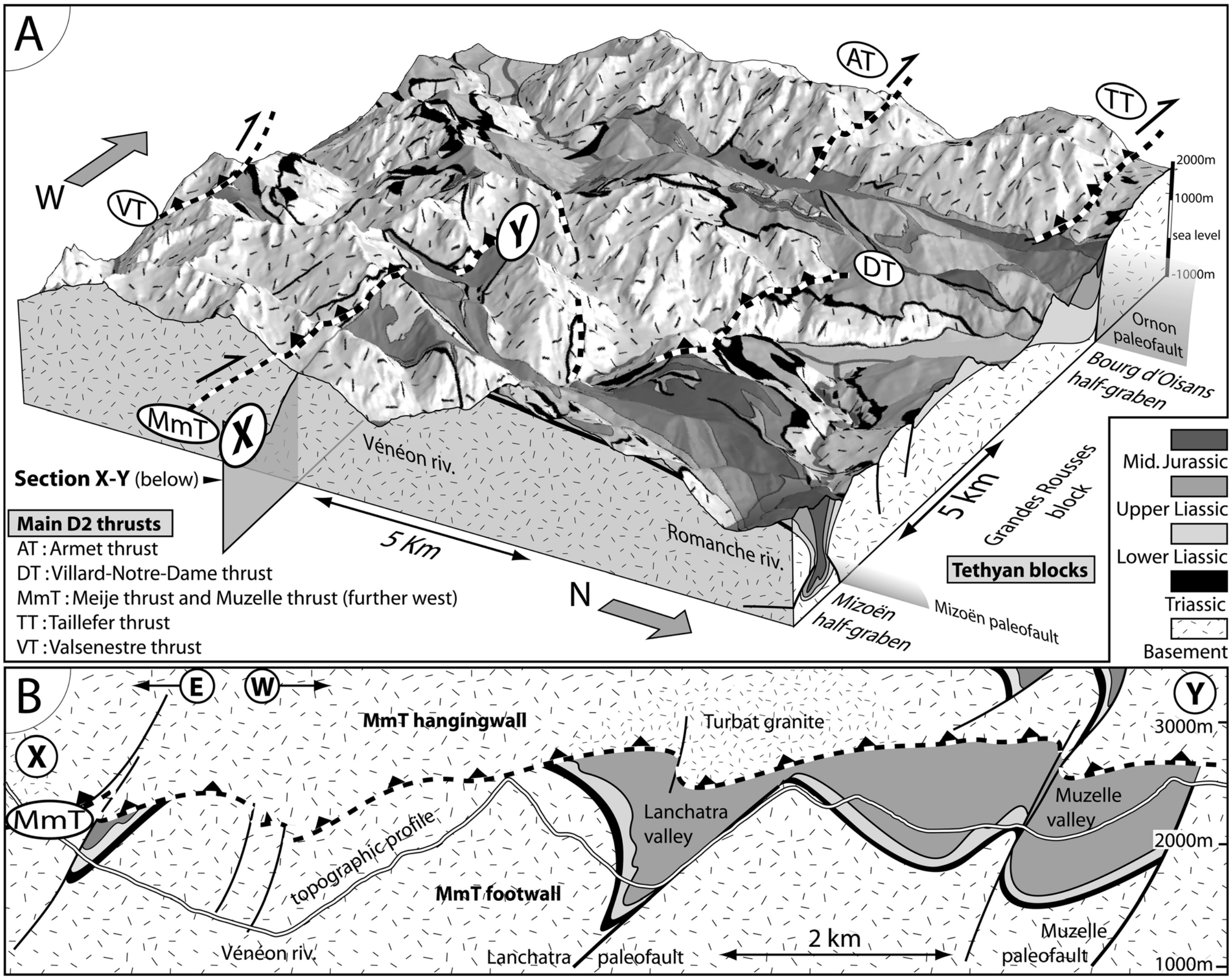

Figure 9. Interferences between Tethyan blocks and perpendicular D2 and D3 shortening phases in Oisans area. (a) A set of E-W-trending, north-directed D2 high-angle basement-involved thrusts cross-cuts and offsets the N-S-trending Tethyan tilted blocks. (b) The X-Y section showing that the Tethyan tilted blocks and the D2 Meije-Muzelle thrust (MmT) were affected together by D3 E-W shortening.

consistent with the African plate over a south-dipping continental subduction zone, to provide flexural loading of the European lithosphere. The lateral termination and confinement of the Alpine Paleogene flexural basin occurs in Haute Provence, with local westward facies migration [*Sztrákos and Du Fornel*, 2003; *Du Fornel et al.*, 2004; *Puigdefàbregas et al.*, 2004]. Even there, northward to northwestward propagation of deformation is recorded during the late Eocene (southern margin of St Antonin basin [*Stanley*, 1980; *Tempier*, 1987]).

[35] The propagation of the early nappes stack (EN) was preceded by soft-sediment deformation and the widespread and diachronous emplacement of olistostromes on top of the Paleogene series [*Kerckhove*, 1969; *Mercier de Lépinay and Feinberg*, 1982]. The occurrence of synsedimentary tectonics related to thin-skinned compressional deformation of the basin has been proposed by *Apps et al.* [2004] with a SW-ward polarity, which contradicts the SE-NW flexural gradient. Actually, the Grès d'Annot provide evidences of NW-directed basin floor deformation, i.e., northwest- or southeast-directed onlaps [*Ravenne et al.*, 1987; *Euzen et al.*, 2004; *Smith and Joseph*, 2004] or sequences architecture [*Broucke et al.*, 2004].

[36] A key feature, up to now underestimated, is the occurrence of large-wavelength removal of the Paleogene section prior to the first Embrunais Nappes emplacement. This removal occurred in a basinal setting as demonstrated by the permanent occurrence of the olistostrome over it. It has been attributed to basin floor incision by canyons, providing a depleted area between the Pelvoux and Argentera highs in which the Embrunais nappes were subsequently emplaced [*Kerckhove*, 1969], but this interpretation is questionable considering the recent exhumation ages of these massifs [*van der Beek et al.*, 2010; *Bigot-Cormier et al.*, 2006]. Alternatively, a NW-SE cross-section (Figures 12a and 12b) shows that complete removal of the Paleogene section occurs over large wavelength anticlines corresponding to the Embrun half-window and to the Barcelonette window, an area also featured by thick Jurassic series of the Vocontian basin. This suggests that removal was caused by uplift due to an incipient structural inversion of the basin. A link between compressional deformation, basin floor

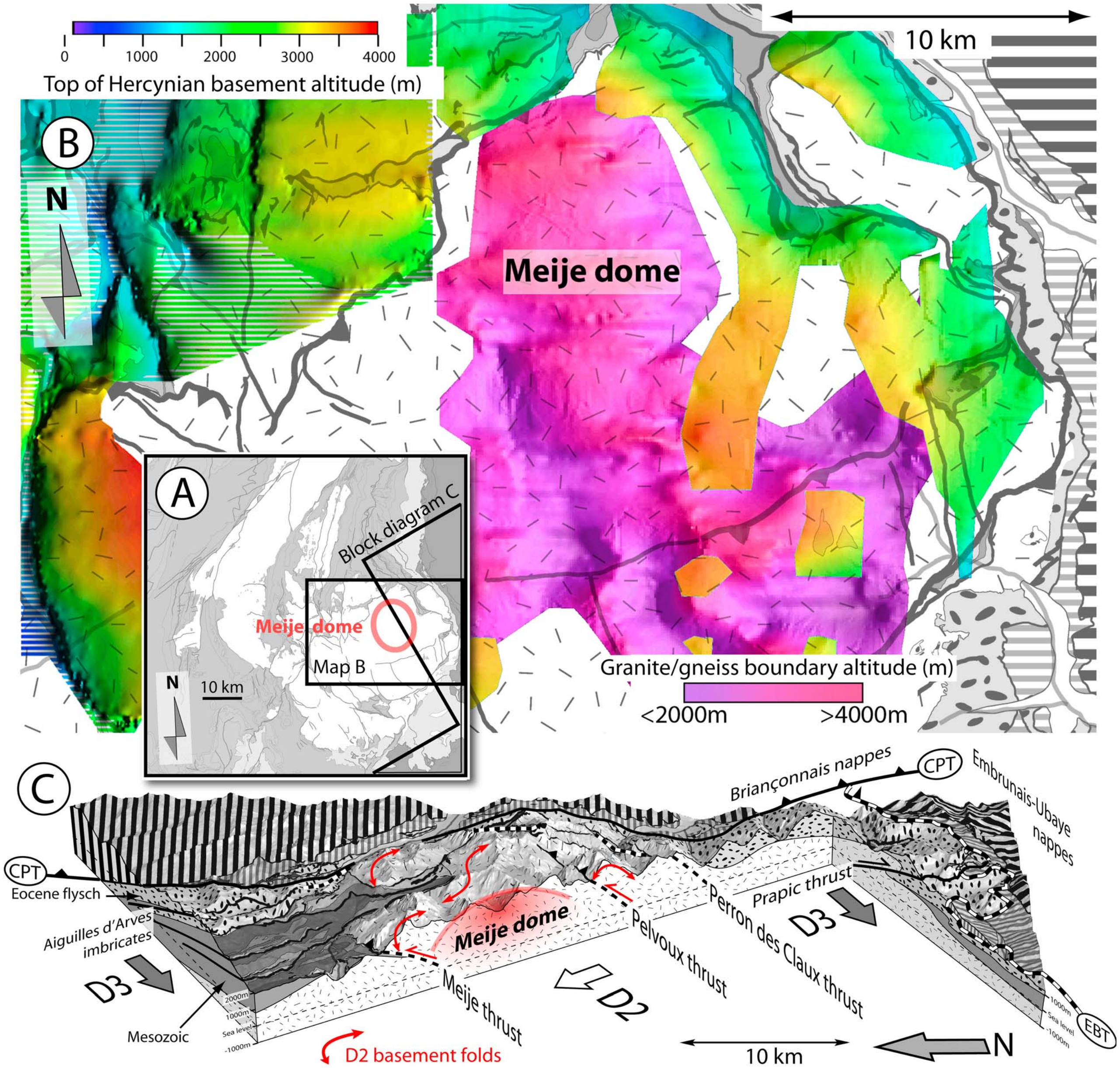

Figure 10. Interference between D2 and D3 perpendicular shortening phases marked in the central Pelvoux basement. (a) Location map. (b) The ~10 km wavelength doming of the interface between the granite and the gneissic envelope (purple shaded surface). Similar doming affects the basement-Mesozoic interface (rainbow shaded surface), which shows that the Meije dome is an Alpine structure. Background: same legend as Figure 1. (c) Block diagram showing perpendicular sections following the D2 and D3 transport directions (SE-NW and NE-SW, respectively). The SE-NW section is more appropriate to illustrate the D2 folds and thrusts. Same mapping legend as Figure 1.

tilting and further removal of Paleogene series is observed at the southern margin of this area, to the SE of Barcelonette. The eastern part of the Barcelonette window is cored by a tight, northward recumbent anticline (Terre Plaine fold, Figure 12c) on which the Paleogene series is absent. The southern limb of this fold, involving the southestward-tilted Globigerina marls, is onlapped by the lower half of the Grès d'Annot formation: this is demonstrated by a conglomeratic marker layer usually found in the middle part of the formation, which rests with angular unconformity on the Globigerina marls along the road from Jausiers to Restefond pass, at an altitude of 2050 m (location a, Figure 12d) [*Kerckhove*, 1974]. The upper half of the Grès d'Annot formation is truncated NW-ward by the olistostrome from this altitude to the Restefond pass. This truncation follows soft-sediment deformation and syn-depositional faulting in the Grès d'Annot further southeast [*Bouroullec et al.*, 2004]. The resulting NW-directed paleoslope, which is still visible in the landscape (Figures 12d and 13), is covered by kilometric-scale blocks derived from the Briançonnais-Provence realm,

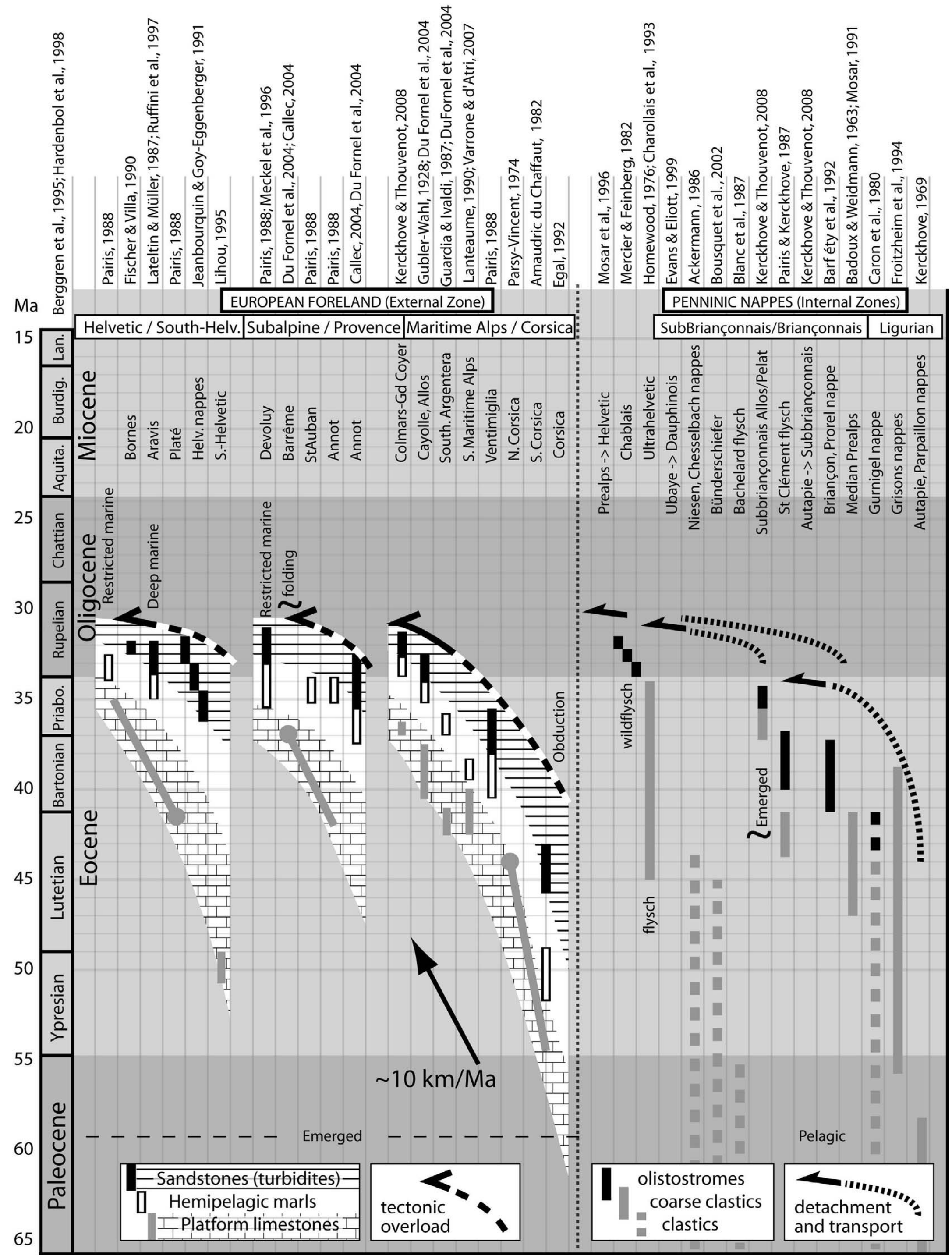

Figure 11. Stratigraphic record of the NW-ward propagation of the Paleogene flexural basin over the proximal margin (European foreland) and the distal margin (Penninic nappes), from literature review. The flexural basin floor consists of a continental erosional unconformity over the proximal margin. This erosion is primarily a result of the regional uplift related to the Iberian plate sinistral transpressive motion. The emplacement of the nappes and the closure of the basin occurred from late Eocene (distal margin and Corsica) to early Oligocene (proximal foreland), whereas Alpine collision was active till Miocene.

each of them showing different stratigraphic characteristics. Similar olistoliths of Briançonnais origin are described further SE, to the SE of the Argentera massif [*Lanteaume*, 1990]. In the study area, some of these include Upper Jurassic reefal limestones (b, Figure 12d), which indicates a southern provenance and which is consistent with the interpretation of gravity sliding from the inverted northern edge of the Provence platform. Moreover, relicts of the

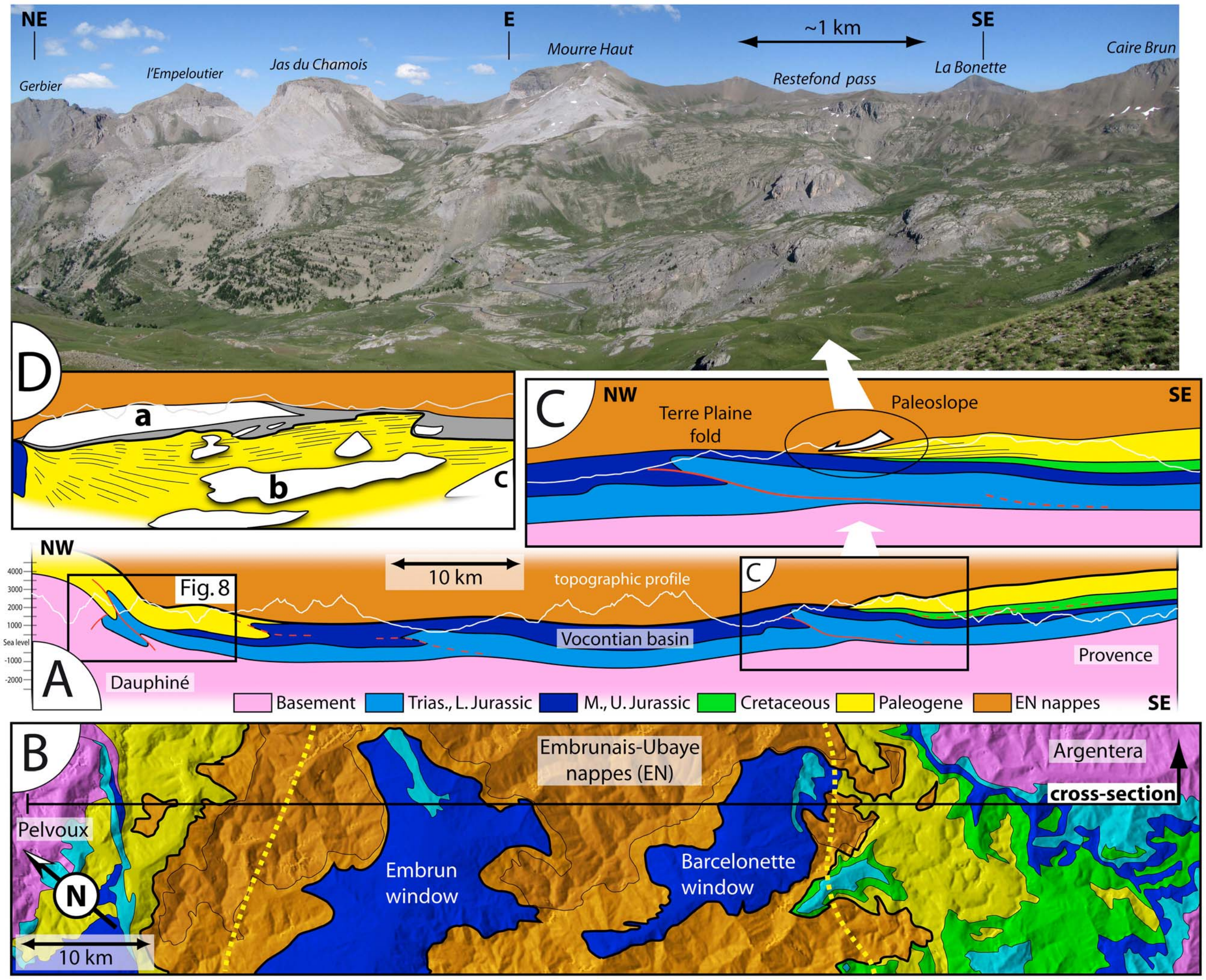

Figure 12. Evidence for basin-floor folding during the infill of the Paleogene flexural basin, to the SE of the Pelvoux area. (a) A SE-NW cross-section between the Pelvoux and Argentera massifs crosscuts two tectonic windows beneath the Embrunais Nappes (Figure 12b), which correspond to large-wavelength anticlines. (b) The Paleogene flysch sediments (Champsaur sandstones formation to the NW, Annot sandstones formation to the SE) are missing due to early Oligocene erosion in the central area, between the yellow dashed lines. (c) The Barcelonette window is cored by a N-recumbent fold (Terre-Plaine fold) above which the Paleogene flysch sediments are onlapping northward the Mesozoic formations. (d) The >600 m thick Annot Sandstones formation is truncated and removed northward by a NW-dipping submarine paleoslope covered by an olistostrome and by plurikilometric blocks issued from southern (Briançonnais to Provence) paleogeographic domains (photograph, northern slope of Restefond pass, and Figure 13). These mega-blocks are a, the Mourre Haut unit with Provence-type reefal upper Jurassic facies, b, the Roche Madeleine unit with Subbriançonnais-type serie, and c, the Roche Chevalière unit with highly condensed, Briançonnais-type series. Note the downward (NW-ward) truncation of the underlying Annot sandstone beds, which is inconsistent with a tectonic emplacement of these units. Basin-floor folding, submarine erosion or slump-scar, and gravity sliding indicate a SE provenance and a NW-ward propagation of the early Alpine accretionary buildup in the southern part of Western Alps. This orientation and the age of these events are consistent with deformation D2 in the Pelvoux area.

platform-basin transition (with a SE-NW polarity) are transported in the Morgon nappe stack (W of Barcelonette), presently overlying the Vocontian basin series [*Kerckhove*, 1974].

[37] Both onlap and truncation of the Grès d'Annot demonstrate the occurrence of northward-recumbent folding during and soon after the infill of the flexural basin, that is, during Priabonian to early Oligocene times. Together with north-directed inversion of the northern edge of the Provence platform, these sedimentological features are consistent with those observed in Dauphiné (section 3.3) and with NW-directed basement thrusting documented in the Pelvoux area.

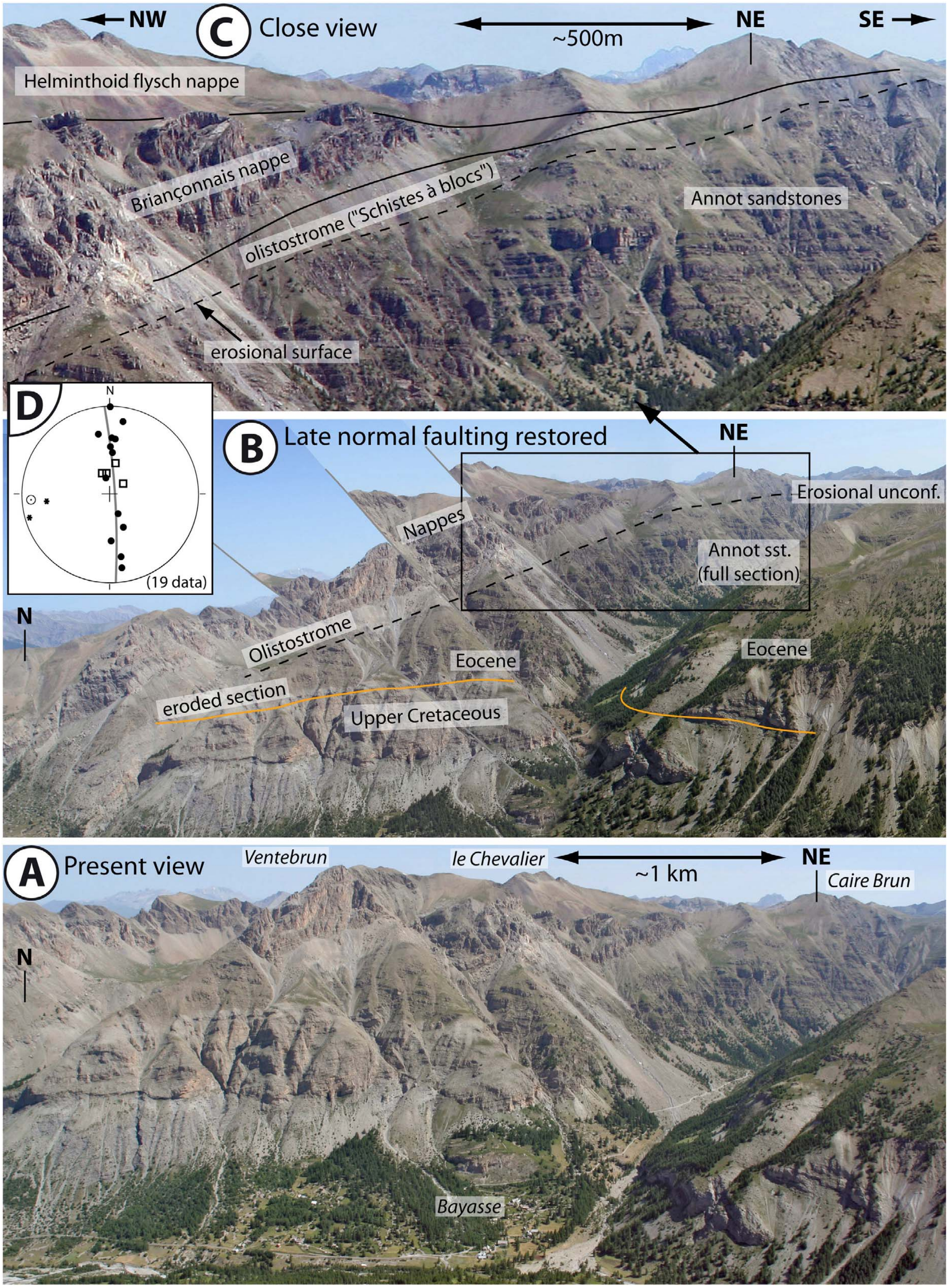
NW
C Close view
~500m
NE
SE
Helminthoid flysch nappe
Briançonnais nappe
olistostrome ("Schistes à blocs")
Annot sandstones
erosional surface
D
N
(19 data)
B Late normal faulting restored
NE
Erosional unconf.
Nappes
Annot sst. (full section)
N
Olistostrome
Eocene
Eocene
eroded section
Upper Cretaceous
A Present view
Ventebrun
le Chevalier
~1 km
NE
Caire Brun
N
Bayasse

Figure 13

4.2. Renewed Distribution of Foreland Basins During Early Oligocene

[38] By early Oligocene times, the distribution of syn-orogenic sedimentation changed completely in the Subalpine domain [*Ford et al.*, 2006]: most of the previously subsiding areas of the Paleogene flexural basin were either included in the orogen or passively uplifted in the hanging wall of new westward propagating thrusts (Pelvoux area and Digne nappe). By contrast, some continental or lacustrine depocenters developed in the proximal footwall of the Digne nappe, which was previously devoid of sedimentation. Despite this subsidence inversion, the Paleogene flysch sequence, pinching out westward, is locally overlapped by the westward thickening Oligocene molasse deposits [*Meckel et al.*, 1996]. However, the contact is frequently unconformable and marked by an erosional surface, and flysch pebbles are found in the molasse sequence. At least locally (Barrême syncline), a ~90° shift in sedimentary transport directions occurred during the early Oligocene, from north-directed in the Grès de Ville formation to E-W in the Clumanc conglomerates formation [*Callec*, 2001]. The latter record the first early Oligocene occurrences of blueschist pebbles derived from rapidly exhumed portions of the previously developed accretionary prism, both on the French side [*Chauveau and Lemoine*, 1961; *Evans and Mange-Rajetsky*, 1991; *Morag et al.*, 2008], and in the Tertiary Piedmont basin [*Polino et al.*, 1991; *Cibin et al.*, 2003]. The Tertiary Piedmont Basin exhibits a sharp erosional unconformity which truncates highly deformed Alpine nappes, and was overlain by coarse continental clastics during the early Oligocene [*Carrapa et al.*, 2004; *Di Giulio et al.*, 2001; *Marroni et al.*, 2002]. This unconformity is coeval with the re-organization observed on the French side, above the Paleogene flexural basin infill.

[39] The Oligocene setting is characterized by a completely renewed drainage pattern as indicated by the first occurrence of oceanic basement and blueschist pebbles issued from the Internal Zones in the western foreland [*Chauveau and Lemoine*, 1961; *Evans and Eliott*, 1999]. Westward propagation of deformation is recorded by the sediments in several areas: (1) top-to-the west syndepositional folding occurred as soon as 31 Ma ago in the Barême thrust-top syncline [*Artoni and Meckel*, 1998; *Callec*, 2001] and (2) westward to northwestward directed thrusting occurred prior to or during the deposition of the Rupelian "Molasse Rouge" formation in the Digne area (Esclangon thrust sheet [*Haccard et al.*, 1989]) and in the Faucon du Caire area (Roche Cline thrust sheets [*Arnaud et al.*, 1978]). A westward shift of depocenters is observed in Oligo-Miocene times both in the southern Subalpine chains [*Couëffé and Maridet*, 2003] and in the Helvetic realms [*Beck et al.*, 1998]. Much younger (Miocene) displacements, partly gravity-driven, occurred toward the SSW in the Subalpine realm.

[40] Nevertheless, subsidence inversions and changes in clastics provenance, in the trends of syn-depositional deformation and in the direction of displacements of facies and depocenters are consistent with the occurrence of a sharp kinematic change during early Oligocene times. The age of this event can be bracketed within a short time interval between the youngest deposits of the flexural flysch basin (~31–32 Ma, Figure 11) and the oldest infill in the thrust-top molasse basins (~30–31 Ma [*Artoni and Meckel*, 1998; *Callec*, 2001]).

5. Consistency With the Tectono-metamorphic History of the Internal Arc

5.1. Crustal Record of Continental Subduction During the Eocene

[41] The internal zones exhibit a wide range of European continental margin units which were gradually involved in the subduction channel during the Paleogene. Reviews of geochronological and metamorphic data are provided by several authors [i.e., *Schmid et al.*, 1996; *Rosenbaum and Lister*, 2005; *Berger and Bousquet*, 2008] and the metamorphic structure is compiled by *Bousquet et al.* [2008]. These data indicate that high-pressure metamorphism occurred over a long period until 35 Myr, requiring a specific driving mechanism for subduction to be maintained. The same statement is true for the continental and oceanic units of the Ligurian Alps underlying the Tertiary Piedmont Basin, which suffered HP-LT conditions at different time during the early to middle Eocene subduction [*Capponi and Crispini*, 2002; *Federico et al.*, 2005]. The oceanic units of the Voltri group correspond to a relict of an ophiolitic mélange zone compatible with the occurrence of a serpentinite subduction channel [*Federico et al.*, 2007; *Guillot et al.*, 2009b). Figure 14 shows high-pressure and exhumation ages plotted from some selected references between the oceanic units and the proximal European margin represented by the external zone. Although non-comprehensive, it illustrates the diachroneity of involvement of the distal margin units, especially the Briançonnais domain, in the continental subduction zone. This process covers the same time span as the migration of the Paleogene flexural basin toward the Helvetic foreland (Figure 11), that is the entire Eocene stage. The onset of metamorphism corresponds to the obduction of part of the oceanic accretionary wedge, containing mélanges with contrasting metamorphic grade, over the European margin toe during early Eocene, and the final stage is marked by underthrusting of the proximal margin (external and central Alps basement) beneath the collisional wedge during the early Oligocene. The overlap of high-pressure and brittle exhumation ages in different fragments of the Briançonnais

Figure 13. Lateral view of the regional-scale truncation of the Annot Sandstones formation (Mauvaise Cöte area, SW of Restefond pass. (a) Panoramic view. (b) Late orogenic normal faulting removed to restore the angular unconformity and paleoslope on top of the Annot Sandstones formation (same scale and orientation as Figure 13a). (c) Closer view of the erosional unconformity capped by the olistostrome ("schistes à blocs"), by a Briançonnais "nappe" (more probably a large-scale slided block) and by the Helminthoid Flyschs nappes. (d) Drag folds measured in the near footwall of the nappes toward the toe of the paleoslope, ~4 km further north (Le Sauze resort, 44°20′12,6″N, 6°41′22″E). Legend is the same as in Figure 3. These folds indicate north-directed shear associated with the emplacement of the nappes.

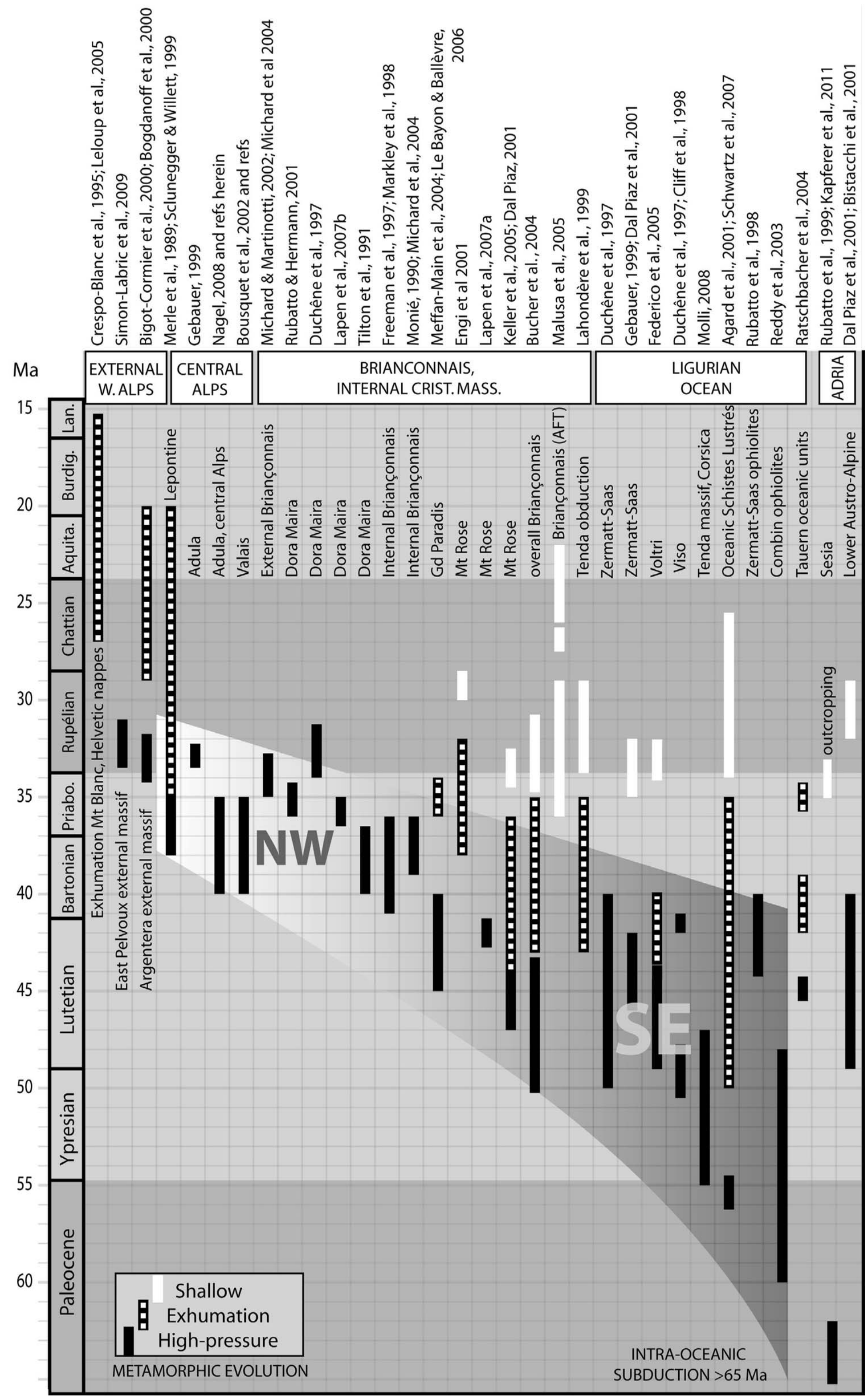

Figure 14. Metamorphic record of the NW-ward propagation of Alpine orogeny in the Internal Nappes stack, from literature review. The distal European margin units (Briançonnais) were gradually involved in continental subduction during more than 15 Ma (middle and upper Eocene). This time span corresponds with the range of propagation of the flexural basin over the proximal European margin (Figure 11). High-pressure deformation reached the External basement massifs in early Oligocene time only, coeval with the final exhumation stages in part of the Internal Zones.

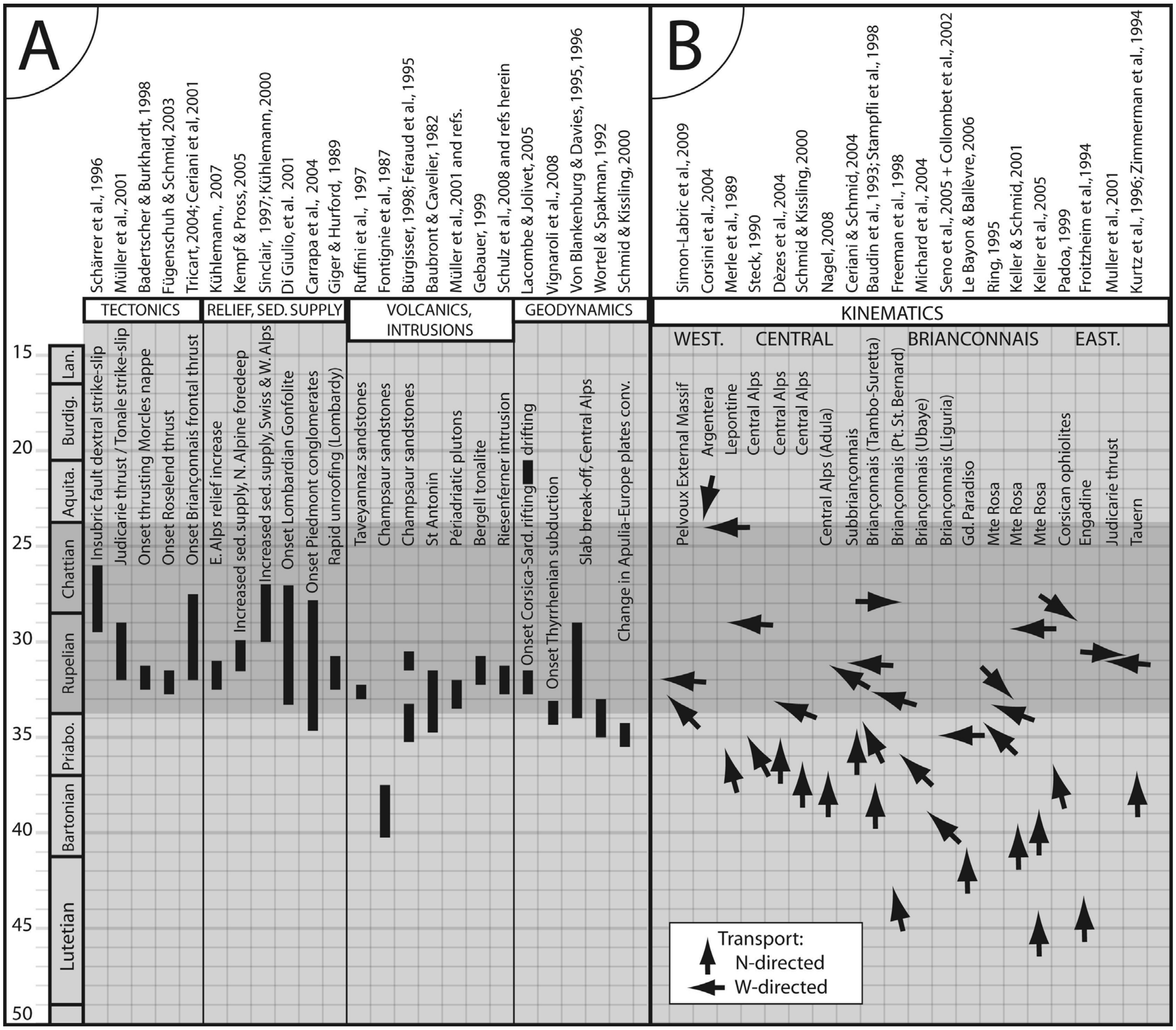

Figure 15. Major early Oligocene events observed in (a) the Alpine realm and (b) kinematic change close to the Eocene-Oligocene boundary from literature review. Black arrows (Figure 15b) indicate the direction of transport criteria (north on top). The Eocene continental subduction stage, corresponding to diachronous high-pressure ages in the Briançonnais units and to landward propagation of the flexural basin, is featured by dominantly north-directed tectonic transports. The abrupt development of westward extrusion in early Oligocene time is marked by anticlockwise rotation in transport directions and/or initiation of backfolding.

crust at that time is in agreement with its gradual accretion in the orogenic wedge. Considering a ~1 cm/yr convergence rate based on geodynamic reconstructions and on structural constraints [*Rosenbaum et al.*, 2002; *Schmid and Kissling*, 2000], the ~150 km wide area predicted to have been consumed during this time period is consistent with the palinspastic width of the Briançonnais terrain [*Lemoine et al.*, 1986; *Stampfli et al.*, 1998, 2002]. In the Voltri paleo-subduction channel [*Federico et al.*, 2007], the initial deformation stage coeval with the eclogitic foliation occurred in Lutetian times [*Capponi and Crispini*, 2002]. One unit shows prograde metamorphism up to 80 km depth associated with top-to-the-NW sense of shear, consistent with a SE-dipping downgoing slab interpretation [*Hermann et al.*, 2000]. The accretion of the lower plate continental fragments (e.g., Briançonnais) to the overriding plate implies a northward component of displacement during their exhumation, which fits the model of *Ricou and Siddans* [1986]. Such displacements are supported by the similarities between the Briançonnais units, presently scattered along the arc, and the Provence-Corsica-Sardinia realm further south, concerning (1) late Paleozoic volcanism and plutonism [*Bertrand et al.*, 2005], (2) external Variscan type Upper Paleozoic series [*Michard and Goffé*, 2005, and references therein], (3) siliciclastic and carbonate Triassic series (Alpes Maritimes [*Lanteaume*, 1990]). This documents the top-to-the north orientation of this Eocene continental subduction system, which fits the propagation of the coeval flexural

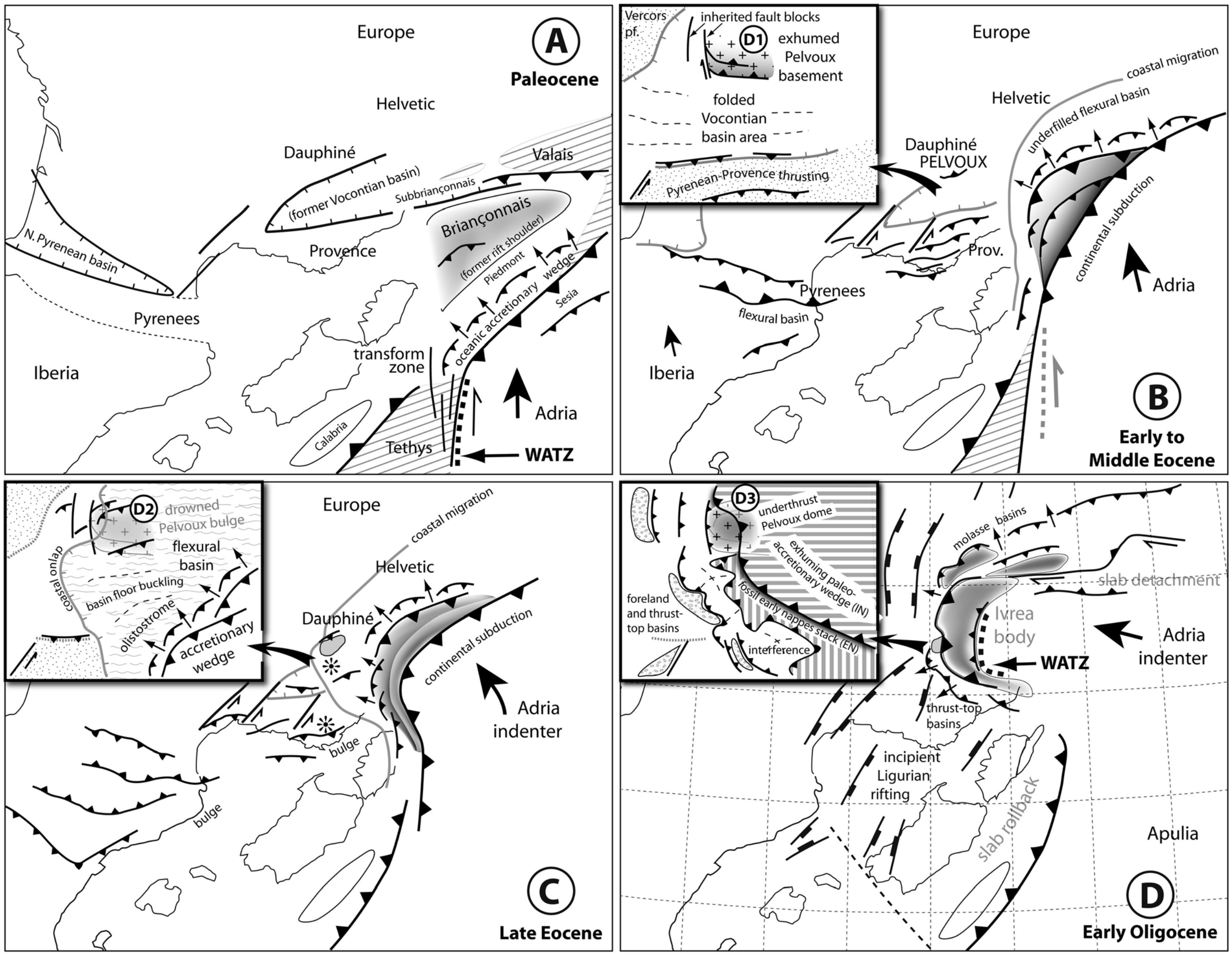

Figure 16. (a) Proposed palispastic evolution of the western Alpine realm and surrounding areas. Before Eocene, the presumed Western Adria Transform Zone (WATZ) bounded a NW-dipping subduction zone beneath the eastern part of the Iberian microplate (including southern Corsica, Sardinia and Calabria but except the Briançonnais), from a SE-dipping zone beneath Adria. The continentward propagation of this transform zone allowed the Briançonnais terrane to be separated from the Iberian plate and integrated in the Alpine accretionary prism, the Adriatic crust and upper mantle therefore overlying the European crust. From early Oligocene onward, the northern part of Adria rotated and moved westward. It is proposed that the rectilinear western boundary of the Ivrea upper mantle indenter which cores the Oligocene to present arc could be a relict of the WATZ. The regional setting of the study area is figurated in the upper left cartoons, with three shortening events having affected the Pelvoux massif. (b) South-vergent thrusts involving the southern Pelvoux area, and bounded westward by the inherited Tethyan fault pattern (deformation D1). (c) North- to NW-vergent thrusts crosscuting the D1 structures, involving the central and northern Pelvoux areas, and bounded westward by inherited faults (deformation D2). (d) Underthrusting of the Pelvoux bulge, previously uplifted by D1 and D2 episodes, beneath the Internal Nappes stack (deformation D3).

basin, but which is strongly oblique to the present geometry of the western Alpine arc.

5.2. The Oligocene Revolution

[42] A wide range of magmatic, structural, morphologic and geodynamic events occurred during early Oligocene times in the whole Alpine realm (Figure 15a). The Periadriatic plutons emplacement occurred between 33 and 31 Ma, and it is regarded as a thermal consequence of slab breakoff in the Central Alps [*von Blanckenburg and Davies*, 1995]. It is roughly coeval with the onset of dextral shear and thrusting along the Periadriatic line segments [*Schmid et al.*, 1989; *Müller et al.*, 2001; *Handy et al.*, 2005]. Calc-alkaline post-collisional volcanics are commonly reworked in the early Oligocene flysch sediments of the flexural basin [*Vuagnat*, 1985; *Waibel*, 1990], and may be related to the same thermal event, although their origin is still debated [e.g., *Garzanti and Malusa*, 2008]. Major crustal thrusts were activated contemporaneously in the Western Alps [*Badertscher and Burkhard*, 1998; *Tricart et al.*, 2001; *Fügenschuh and Schmid*, 2003; *Simon-Labric et al.*, 2009], which crosscut the previous buildup. A sharp increase in

sediment budget and basins overfill in the northern and western forelands is regarded as a consequence of enhanced elevation of the axial chain [*Kühlemann*, 2000; *Kempf and Pross*, 2005; *Morag et al.*, 2008]. The coeval onset of coarse sedimentation in Lombardy and Piedmont is also probably associated with rapid unroofing in Western and Central Alps [*Giger and Hurford*, 1989; *Carrapa et al.*, 2004]. The correlative burial affecting the previously exposed Eocene HP wedge in Piedmont [*Bertotti et al.*, 2006] exactly balances the exhumation and canibalization of parts of the Eocene flexural basin with its initial overload in the French foreland, providing rapidly exhumed HP clasts in further foreland basins. This coarse clastic sedimentation of early Oligocene age [*Bertotti et al.*, 2006] seals the HP-LT oceanic mélange rocks of the serpentinite subduction channel in the Ligurian domain [*Capponi and Crispini*, 2002; *Federico et al.*, 2007], which implies a major change in the kinematics of the orogen and in the accommodation of convergence at that time.

[43] From a geodynamic point of view, and besides the assumed slab break-off, the early Oligocene also corresponds to the initiation of subsidence in the west European rift system [*Merle and Michon*, 2001], of the Corsica-Sardinia rifting [*Brunet et al.*, 2000; *Lacombe and Jolivet*, 2005], and to the onset of the Tyrrhenian-Apenninic dynamics [*Doglioni et al.*, 1998; *Gueguen et al.*, 1998]. This lithospheric-scale reorganization is marked by tectonic shifts in most of the Alpine units (Figure 15b). Both in the internal and the external zones of the western Alpine arc, the trend of stretching lineations resulting from tectonic transport varies through time, showing anticlockwise rotation as described by *Platt et al.* [1989b] in the Briançonnais nappes. The early deformation in the internal zones are dominantly north-directed, associated with transverse folds [*Caby*, 1973] and pervasive D1 transport lineations [*Carry*, 2007], and have been re-arranged by arcuate bending during later episodes [*Rosenbaum and Lister*, 2005; *Handy et al.*, 2010]. After the tectonic shift near the Eocene-Oligocene boundary, the tectonic transport directions vary from NW to SW, with some backfolding in the core of the arc, and interference features occurred [*Steck*, 1998; *Ganne et al.*, 2005]. In the external zone, there is an increasing discrepancy between the early and late Alpine transport directions, from <45° in the northern part of the arc (Prealps and Helvetic nappes [*Dietrich and Durney*, 1986; *Ramsay*, 1989; *Mosar et al.*, 1996]; Northern Subalpine massifs [*Wildi and Huggenberger*, 1993] to 90° and more in the southern part (southern Pelvoux, southern Subalpine domain; this study).

[44] As opposed to the diachronous character of the propagation of continental subduction and lithospheric flexure during Eocene times, the early Oligocene event seems to have affected simultaneously the whole Alpine realm, with drastic kinematic, morphologic and tectono-sedimentary consequences requiring a first-order geodynamic cause.

6. Discussion and Conclusion

[45] The central and southern parts of the External Western Alps show evidence of interference deformation and shortening during Alpine collision. The Pelvoux large-scale cross-fold probably developed over a basement ridge perpendicular to the present chain, and the southern Subalpine Meso-Cenozoic cover shows basin-and-swell structures (Remollon and Barrot domes, Embrun and Barcelonette tectonic windows) which result from interfering shortening events. As this area belonged to the northern foreland of the Pyrenean-Provence orogeny during early Tertiary [*Dèzes et al.*, 2004], such interferences have been previously regarded as superposed effects of the dynamics of the Iberian and Apulian plates. However, our analysis demonstrates that part of "orogen-parallel" shortening in the southern foreland of the western Alpine arc actually relates to the early stages of the Apulian collision, because it post-dates the onset of flexural loading of the European foreland by the Adriatic wedge. Both near-surface evidence in the Paleogene flexural basin, such as synsedimentary folding, gravity sliding and submarine slope scar, and upper crustal deformation in the Dauphiné external basement document a top-to-the north-west direction of propagation of the collisional thrust stack during the Eocene. Consistently, the published kinematic data from the internal arc show that the early, high-pressure deformation occurred mainly in a northward propagating setting before the early Oligocene. The diachroneity of high-pressure ages within the distal part of the subducted plate (Briançonnais domain; Figure 14) is best explained by a continental subduction regime spanning the entire Eocene, which is coeval with the flexural basin propagation. A relict of a serpentinite subduction channel is exposed close to the Alps-Apennine junction [*Federico et al.*, 2007], whose activity during the Eocene fits well this north- to NW-vergent continental subduction setting. Continental subduction also explains the consistency between the propagation rate of the flexural basin (section 4.1), the subduction rate of the continental margin fragments of the lower plate [*Berger and Bousquet*, 2008] and the Africa-Europe convergence rate of about 1 cm/yr, provided that the Adria microplate remained joined to Africa at that time, which still remains highly debatable [e.g., *Handy et al.*, 2010]. The docking of the subducted fragments to the accretionary wedge caused large-scale northward to northwestward displacements, which must be taken into account for palinspastic restoration of the northern Tethyan margin, especially for the Briançonnais realm.

[46] For reasons which are still debated, a complete renewal of the tectonic setting occurred close to the Eocene-Oligocene boundary, initiating a mature stage of collision with westward escape of the internal nappe stack. As a result, the deepest part of the paleo-accretionary wedge was crosscut and either rapidly exhumed (Ligurian Alps, Voltri group), or thrust laterally over the proximal part of the flexural basin, allowing a metamorphic rocks provenance for the synorogenic sediments during the early Oligocene on both sides of the present orogen. The truncation of the subduction channel relicts by the molasse sedimentation in the Ligurian Alps [*Federico et al.*, 2007] is a testimony of the abrupt change in dynamics of the chain. This scenario is summarized in Figure 16, which was constructed using both paleogeographical and paleostructural constraints from the literature (i.e., coastal migration of the flexural basin after *Ford et al.* [2006] and estimated location of the Adriatic

microplate after the sequential restoration of *Schmid and Kissling* [2000]). More open choices are included such as the western closure of the Valais ocean and the occurrence of a N-S transform zone which bounds the NW-dipping subduction beneath the Sardinia-Calabria-Corsica (pp.) block (Figure 16a). The formation of the western Alpine arc discussed in this paper is a key feature of this restoration: following many authors [*Ziegler*, 1989; *Stampfli et al.*, 2002; *Rosenbaum and Lister*, 2005; *Ford et al.*, 2006; *Molli*, 2008; this study], it occurred mostly after Eocene times, and is thus a consequence of the mature collision stage and of lateral extrusion. The location of the arc seems to have been influenced by the western termination of the Eocene flexural basin (Figures 16b and 16c), with coastal migration propagating westward and southwestward in SE France [*Puigdefàbregas et al.*, 2004]. This lateral termination can be understood provided that the Apulia upper plate, responsible for flexural loading, did not extend westward farther than the present location of the Ligurian Alps (Figures 16b and 16c). Thus, we hypothesize the occurrence of a major N-S transform boundary with subduction polarity reversal between (1) the northwestward-dipping subduction below the eastern part of the Iberian plate (Calabria, Sardinia, Corsica p.p.) consistent with the propositions of *Padoa et al.* [2001], *Durand-Delga and Rossi* [2002], *Faccenna et al.* [2004], *Lacombe and Jolivet* [2005] or *Vignaroli et al.* [2008] and (2) the southeast-dipping Alpine subduction below Adria. We propose to name it the Western Adria Transform Zone, or WATZ (Figure 16a). As initially proposed by *Ricou and Siddans* [1986], such a sinistral transform boundary allows the Briançonnais domain to be detached from its Iberian motherland (the Sardinia-Corsica realm) and dragged beneath the northward-propagating Adria plate. The northward drift of Adria produced initial thrusting of the oceanic accretionary wedge (so-called Schistes Lustrés) over the distal European margin, namely the Piedmont and internal Briançonnais domains, then the gradual involvement of Briançonnais fragments in the Tethyan subduction zone, and finally the activation of a secondary subduction zone between the Briançonnais and the Valais attenuated crust further north [*Handy et al.*, 2010]. This northward motion of Adria also gave the opportunity to prepare the superposition of Adriatic and European lithospheric mantles, a duplication which is well documented in the Western Alps [*Lardeaux et al.*, 2006].

[47] From the early Oligocene onward (Figure 16d), the northern part of Adria was translated westward, pinching the accretionary buildup derived from the previous stage in between the western Alpine foreland and the uplifted western limit of the Adriatic lithosphere. The "Schistes Lustrés" fossil accretionary wedge therefore suffered E-W ductile to brittle extensional shear during exhumation and tilting [*Schwartz et al.*, 2009]. The Oligocene Western Alpine evolution resulted primarily in the combined effects of two related dynamics: (1) westward indentation (combined with anticlockwise rotation [*Channell*, 1996]) of previously uplifted Adriatic lithospheric mantle to the north (Ivrea body), and (2) SE- to east-directed incipient Apenninic thrusting to the south, probably driven by slab rollback beneath the Corsica-Sardinia-Provence realm suffering back-arc extension [*Faccenna et al.*, 2004]. The contrasting evolution of these two domains led to strain partitioning and the necessary development of strike-slip boundaries [*Malusà et al.*, 2009].

[48] Our model may furthermore provide a link between the geodynamic behavior of these two domains: the abrupt eastern termination of the slab underlying Corsica-Sardinia-Provence, corresponding to the WATZ, is expected to have generated a toroidal, anticlockwise asthenospheric mantle flow as soon as the rollback process started [*Jolivet et al.*, 2009], that is during Oligocene. This may have enhanced the northward drift of the Adriatic lithosphere and its anticlockwise rotation at that time. Its northwestern part corresponds to the Ivrea body, which has been extensively investigated using geophysical methods [*Roure et al.*, 1996; *Schreiber et al.*, 2010, and references therein] and which outcrops at the western termination of the Southern Alps [*Siegesmund et al.*, 2008]. This Adriatic lithospheric mantle and crustal fragment overthrusts the European Moho, and its western boundary trends approximately N-S beneath the southern part of the Western Alpine arc [*Waldhauser et al.*, 2002; *Kissling et al.*, 2006; *Lardeaux et al.*, 2006], that is in strong discrepancy with the present arc shape [*Beucher*, 2009]. The lower crustal section outcropping further north yielded Eocene ZFT ages [*Siegesmund et al.*, 2008] which would mark the N-directed thrusting stage [*Handy et al.*, 1991] over the oceanic (Sesia) and continental European crust (Briançonnais).

[49] We propose that the N-S trend of the Ivrea lithospheric mantle body which appears roughly rectilinear at ~15 km depth [*Vernant et al.*, 2002] could be a relict of the western transform boundary of Adria during northward Eocene drift (WATZ, Figure 16). The westward motion of this presumably inherited Adria indenter was accommodated by dextral shear along the Periadriatic line as soon as earliest Oligocene [*Handy et al.*, 2005]. A conjugate sinistral shear zone is required to the south, toward the Alps-Apennines junction, from which the recently active "Stura couloir" identified through seismotectonic evidence [*Giglia et al.*, 1996] could derive. The Ivrea body indentation is kinematically linked with the Insubric line activation [*Schmid et al.*, 1987] and with both westward escape in the western arc and the Adriatic plate motion [*Kissling et al.*, 2006]. It produced fast exhumation of the Eocene paleo-accretionary wedge, together with a dramatic increase in altitude and erosion rates. This exhumation is recorded within the lower Oligocene molasse basins on both sides of the renewed relief, sourced from high-pressure metamorphic rocks and oceanic mélanges of various metamorphic grades. The curvature of the arc was progressively acquired, producing radial spreading of transport lineations [*Platt et al.*, 1989b; *Lickorish et al.*, 2002] and southward increasing counter-clockwise rotations of internal units [*Collombet et al.*, 2002]. The southern part of the arc crosscuts perpendicularly the paleo-accretionary wedge. The effects of Oligocene indentation were enhanced at the southern termination of the arc by the onset of Corsica-Sardinia rifting [*Guennoc et al.*, 2000] presumably due to rollback of the NW-ward subducted Tethyan lithosphere [*Faccenna et al.*, 2004; *Jolivet et al.*, 2009]. The Oligocene renewal of the Alpine kinematics thus coincides with the onset of the Mediterranean dynamics.

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